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**Evaluation of Waterborne Radon Impact on Indoor
Air Quality and Assessment of Control Options**

Envirodyne Engineers, Inc., St. Louis, MO

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**EVALUATION OF
WATERBORNE RADON IMPACT
ON INDOOR AIR QUALITY AND
ASSESSMENT OF CONTROL OPTIONS**

By

Albert P. Becker, III
Thomas M. Lachajczyk
Envirodyne Engineers, Inc.
St. Louis, Missouri 63146

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Project Officer: John Ruppertsberger
Hazardous Air and Industrial Technology Branch
Industrial Environmental Research Laboratory
Research Triangle Park, NC 27711

INDUSTRIAL ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
RESEARCH TRIANGLE PARK, NC 27711

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ABSTRACT

This research program was conducted with two objectives:
1) evaluation of waterborne radon impacts on indoor air quality,
and 2) assessment of available control technologies to limit indoor
exposures to radon and its decay products.

This report contains a review of radon's physical, chemical
and radiological properties; a summary of its decay chain; and a
synopsis of health risks, existing regulations, and recommendations
concerning exposure to radon and progeny. Although the report is
primarily concerned with air concentrations of radon and progeny
resulting from waterborne sources, other potential sources (home
subsurface, construction materials, fuel and ambient air) and their
potential impacts on indoor air quality are also discussed.

This report represents results of a literature search con-
ducted to identify and summarize research by investigators in the
United States and foreign countries concerning the concentration of
waterborne radon (C_w) and its effect on the indoor air concentra-
tion of radon (C_a). The major factors which influence C_a/C_w
(including ventilation rate, water transfer efficiency, water use
rates, and volume of the home) are examined. Sensitivity analyses
are conducted to mathematically define a representative value for
 C_a/C_w (0.7×10^{-4}) and its reasonable bounds (0.17×10^{-4} to $3.5 \times$
 10^{-4}).

This report also presents assessments of reported techniques
for removal of radon from water or indoor air. Techniques evalu-
ated for removal of radon from water include decay, aeration and
granular activated carbon. Techniques evaluated for removal of
radon and/or progeny from air include circulation, various types of
ventilation, filtration, electrostatic precipitation, charcoal
adsorption, chemical reaction, and space charging. Where the
reports examined include a sufficient amount of information to do
so, an evaluation of the cost, efficiency and practicality of each
technique is provided.

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ABBREVIATIONS

cm - centimeter
d - day
g - grams
GAC - granular activated carbon
GPD - gallons per day
hr - hour
hr⁻¹ - inverse hours
ICRP - International Commission on Radiological Protection
J - joules
J/g - joules per gram
J/°C-m³ - joules per degree centigrade-cubic meter
kg - kilogram
kg/m³ - kilogram per cubic meter
kPa - thousand pascals
l - liter
l/hr - liters per hour
m - meter
m² - square meter
m³ - cubic meter
m²/g - square meters per gram
m³/s - cubic meters per second
m³/hr - cubic meters per hour
MeV - million electron volts
min - minute
mm - millimeter
MWTP - municipal water treatment plant

ABBREVIATIONS
(Continued)

nCi/m³ - nanocuries per cubic meter
NCRP - National Council on Radiation Protection and Measurement
NTP - normal temperature and pressure
#/cm³ - number per cubic centimeter
pCi - picocuries
pCi/g - picocuries per gram
pCi/l - picocuries per liter
pCi/l/min - picocuries per liter per minute
pCi/m²-s - picocuries per square meter-second
ppb - parts per billion
ppt - parts per trillion
R.H. - relative humidity
rpm - revolutions per minute
s - second
SCFH - standard cubic feet per hour
sec - second
um - micrometers
us - microseconds
W - watts
WL - working level
y - year

SYMBOLS

- ^{228}Ac - actinium 228
 ^{214}Bi - bismuth 214
 $^{\circ}\text{C}$ - degree centigrade
 C_a - concentration of radon in the air of the home
 C_w - concentration of radon in the water supply of the home
 C_a/C_w - air-to-water concentration ratio
 C_w/C_a - solubility or partition coefficient of radon in water
 E - emanation rate of radon
 f - pollutant transfer efficiency from water to air
 $\text{IF}_6^+\text{SbF}_6^-$ - hexafluoroidine hexafluoroantimonate
 ^{40}K - potassium 40
 λ - ventilation rate in the home
 $\text{O}_2^+\text{SbF}_6^-$ - dioxygenyl hexafluoroantimonate
 ^{210}Pb - lead 210
 ^{214}Pb - lead 214
 ^{214}Po - polonium 214
 ^{218}Po - polonium 218
 ^{226}Ra - radium 226
 ^{228}Ra - radium 228
 Ra A - polonium 218
 Ra B - lead 214
 Ra C - bismuth 214
 Ra C' - polonium 214
 ^{219}Rn - radon 219
 ^{220}Rn - radon 220

SYMBOLS
(Continued)

$\text{RnF}^+\text{SbF}_6^-$ - radon fluoroidine hexafluorantimonate

^{228}Th - thorium 228

^{232}Th - thorium 232

^{208}Tl - thallium 208

^{235}U - uranium 235

^{238}U - uranium 238

V_b - volume of material being tested

V_d - volume of dead space

V_{house} - volume of the house

V_w - average water usage in the home

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1.0 SUMMARY

1.1 BACKGROUND

^{222}Rn is a naturally occurring radioactive elemental gas produced by the decay of ^{226}Ra in the ^{238}U decay series. ^{222}Rn undergoes radioactive decay by emission of alpha particles; its characteristic half-life is 3.82 days. ^{222}Rn decay products include a series of short half-life (30 minutes or shorter) radioactive isotopes commonly referred to as "radon daughters" or "radon progeny." These progeny are solid atoms and are chemically active metals. ^{222}Rn short half-life isotopes include ^{218}Po , ^{214}Pb , ^{214}Bi and ^{214}Po .

Presence of ^{222}Rn and radon progeny in indoor-air is due to various sources. The primary sources of radon in buildings are: the natural presence of radon in soil adjacent to the foundation, radon naturally present in construction materials, and potable water supplies. Other sources are background levels of ^{222}Rn in ambient air, and levels of ^{222}Rn in home heating fuels, but these sources are normally of lesser importance. This report is concerned primarily with waterborne sources of ^{222}Rn , and their impacts on the indoor-air quality of homes.

Varying levels of ^{222}Rn can be found in all groundwater as a decay product of ^{226}Ra in source water and by diffusion of ^{222}Rn from the rock and soil matrix surrounding the water. Numerous investigators have quantified levels of radon in water supplies. In the United States, typical radon levels in potable water generally fall below 2,000 pCi/l, but concentrations exceeding 300,000 pCi/l have been noted. Specific areas shown to have substantially elevated levels of ^{222}Rn in water include portions of Maine, New Hampshire, North Carolina, Texas, Arkansas, Florida and Utah.

Health risks associated with ^{222}Rn and its progeny are related to the inhalation of the progeny and to the alpha particles emitted by ^{218}Po and ^{214}Po deposited in the lung. Exposure of internal body tissues by radioactivity associated with waterborne ^{222}Rn can occur through both ingestion of water, and inhalation of airborne daughter products of ^{222}Rn . However, dose to the lung by inhalation is presently considered to be the limiting factor for defining guidelines for acceptable levels of ^{222}Rn in domestic water or acceptable levels of its progeny in household air.

Because of the importance of the inhalation pathway, various investigators have recently attempted to correlate ^{222}Rn concentrations in water supplies (C_w) with resulting concentrations in the air of typical homes (C_a). If a correlation can be established, then a representative air-to-water concentration ratio (C_a/C_w) could be utilized to assess health risks associated with ^{222}Rn concentrations in water supplies.

The assessment of a representative C_a/C_w for homes involves numerous considerations. The quantities of ^{222}Rn released into a home depend on transfer efficiencies associated with each type of use (which range from <10% to >98%) as well as the quantities of water used. The progeny of ^{222}Rn formed in water stay in the water unless evaporation takes place. However, when ^{222}Rn gas transfers from water to air its progeny are then formed in the air. Thus, the levels of both ^{222}Rn and its progeny in building-air at any time are influenced by several factors which include: rate of ^{222}Rn exhalation from water; residence-time of the ^{222}Rn in a given air-volume; air volume of the building; and building ventilation.

Reduction of exposure levels can be accomplished by removing ^{222}Rn from water supplies, or by removing ^{222}Rn and/or its progeny from building air after the ^{222}Rn has exhaled from water or other sources into building air. Several techniques have been reported.

1.2 OBJECTIVES

This study has two primary objectives. The first objective is to assess the relationships between concentrations of waterborne ^{222}Rn and resulting concentration of ^{222}Rn and progeny in homes in order to recommend a representative air-to-water concentration ratio (C_a/C_w). Towards this goal, the prime factors which influence C_a/C_w have been identified, and the sensitivity of the value of C_a/C_w versus these primary factors has been assessed.

The second primary objective of this study is to evaluate the efficiency, cost and applicability of control technology used to reduce radon and radon progeny levels in residences. The control technologies evaluated include both those used to remove radon from water before it becomes airborne and those used to control airborne concentrations in the home. For radon removal from water, both private and municipal systems were evaluated.

1.3 METHODOLOGY

Sources of information were obtained primarily through a literature search. The literature obtained during the search is identified in the List of References and is supplied to the Project Officer as a part of the project record. In addition, personal communication with several of the authors of the literature cited was conducted in order to clarify information, discuss findings, or obtain additional information.

The report contains a summary of publications by numerous investigators who have attempted to derive and/or measure C_a/C_w . In each case, major assumptions, methodology and results are summarized together with an assessment of potential sources of error or uncertainty. Some tables and graphs cited from other publications have been modified slightly, such as changes in units or symbols, in order to clarify data or provide consistency.

Sensitivity analyses were completed through derivation of a basic steady-state equation which relates C_w to C_a , followed by selection of "typical," "liberal" and "conservative" bounds, based on the literature reviewed, for each parameter represented in the equation. The values for C_a/C_w are then displayed graphically to provide estimates for its range of values. The assessment of control technologies is based on reports published by various investigators, as well as engineering judgments concerning the costs and practicality of each.

2.0 CONCLUSIONS

- 1) Levels of ^{222}Rn in water exceeding approximately 1000 pCi/l have been shown to have a measurable impact on indoor air quality.
- 2) C_a/C_w , the ratio of airborne ^{222}Rn resulting from water supplies to the waterborne concentration of ^{222}Rn , has been reported as low as 0.032×10^{-4} and as high as 59.0×10^{-4} in individual homes.
- 3) Most measurements and estimates of C_a/C_w reported in the literature range from approximately 0.18×10^{-4} to 2.0×10^{-4} .
- 4) The value of C_a/C_w in homes depends primarily on home ventilation rates, volume of the home, volumes, types and diurnal variations in water use, and water-to-air transfer efficiency. In addition, measurement of C_a/C_w can be affected by the types and locations of ^{222}Rn monitoring equipment used, indoor humidity, meteorological conditions, circulation systems and architectural style of the home, experimental errors, and complications due to non-waterborne sources of ^{222}Rn entering the home.
- 5) The value of C_a/C_w as referred to in this report expresses a time- and volume-weighted average which could be used to develop relationships between cumulative exposure rates to residents of homes and resulting health effects. C_a/C_w does not evaluate short-term or site-specific acute exposures.
- 6) Work reported by Hess (He82), based on studies in 18 homes in Maine, provides measured values for C_a/C_w in experiments designed to eliminate some of the variation in C_a/C_w due to ventilation rates, non-waterborne sources and monitoring location. The authors

report $C_a/C_w = (0.8 \pm 0.2) \times 10^{-4}$ for C_a measured by Wrenn detectors in the living room of homes, with ventilation rates standardized to 1.0 hr^{-1} . The authors also report $C_a/C_w = 1.3 \times 10^{-4}$ without standardizing for ventilation rate.

- 7) Sensitivity analyses completed for this report suggest that when a typical range of values for ventilation rate, water-to-air transfer efficiency, and ratio of water use to home volume are assumed, C_a/C_w may be expected to have an average value of 0.7×10^{-4} and a range of 0.17×10^{-4} to 3.5×10^{-4} .
- 8) The value of C_a/C_w is likely to vary over a range of approximately one order of magnitude in most domestic situations due primarily to sporadic water use, location of monitoring sites with respect of waterborne ^{222}Rn sources, and fluctuating ventilation rates.
- 9) Presence of radon progeny is more directly responsible for health effects than is ^{222}Rn gas. The concentration of radon progeny in air due to waterborne sources, measured in working levels, has not been investigated to the extent C_a/C_w has been investigated.
- 10) Removal of ^{222}Rn from water can be accomplished through decay, aeration, or carbon adsorption. Efficiencies exceeding 90 percent have been reported to be achievable through each technique. Based on a limited amount of data available concerning the cost, efficiency and practical operability of each technique, carbon adsorption appears to be the most viable choice for most domestic applications.
- 11) Removal of radon and/or radon progeny from indoor air has been demonstrated through circulation, various types of ventilation, filtration, electrostatic precipitation, and charcoal adsorption.

Removal efficiencies of 50 to 95 percent have been reported. Removal efficiencies are dependent on ventilation rates, circulation systems, degree of plate-out occurring, humidity, particle size distribution, and other factors. Selection of control systems for individual homes, based on efficiency, cost and practicality, is highly site-specific and would depend upon the heating, cooling and circulation systems already in place.

3.0 RECOMMENDATIONS

- 1) The value of C_a/C_w is based on theoretical calculations and/or measurements at relatively small numbers of homes. An expanded monitoring program, using standardized monitoring techniques in a cross-section of geographic areas of the United States, may be desirable.
- 2) Further monitoring, if conducted, should be designed and implemented to reduce and quantify uncertainties in C_a/C_w which result from sampling procedures, monitoring locations, measurement of ventilation rates, circulation patterns within the home, meteorological influences, inadequate water use records, diurnal and seasonal variations, contributions from sources other than water, etc.
- 3) Further research in the relationships between the concentration of radon in water and resulting concentrations of progeny in air is required.
- 4) Exposure of an individual to progeny during periods of close proximity to the waterborne source has not been fully evaluated. Dose rates, variations in working levels, and effects on cumulative exposures to progeny should be more fully evaluated.
- 5) The cost, efficiency and practicality of various control technologies, particularly for removal of ^{222}Rn and progeny from air, requires further evaluation.

4.0 GENERAL CONCEPTS AND PROPERTIES OF RADON

This chapter provides an overview of the general concepts and properties of radon to provide an understanding of the basic concepts referenced subsequently in this report.

4.1 PHYSICAL AND CHEMICAL PROPERTIES

Radon, element No. 86, is a naturally occurring radioactive gas. It is a colorless, odorless, chemically inert, noble gas. There are three isotopes of this element in nature, each one associated with a separate family of radioisotopes naturally present in the earth's crustal rock and soil. Those radon isotopes are: 1) ^{219}Rn , descendent from ^{235}U ; 2) ^{220}Rn , descendent from ^{232}Th ; and 3) ^{222}Rn , descendent from ^{238}U . The isotope ^{222}Rn is the most abundant in groundwater and in domestic water supplies. The main reason that the other two isotopes are not significantly present in this water is their short half-lives (4.0 seconds for ^{219}Rn , 55 seconds for ^{220}Rn). The 5500-minute half-life (3.82 days) of ^{222}Rn means it "lives" in the source water a sufficient time to reach the points of water utilization.

Since uranium is relatively abundant and widely distributed in crustal rock and soil, so is its ^{222}Rn descendent. However, the levels of ^{222}Rn in source-water varies from place-to-place by several orders of magnitude. Table 4-1 presents some of the typical properties of ^{222}Rn .

In the remainder of this report, any general use of the word "radon" refers to ^{222}Rn .

One important parameter given in Table 4-1 is the solubility coefficient. The solubility coefficient or partition coefficient in water is defined as the ratio C_w/C_a , where C_w and C_a are the radon concentrations in water and air, respectively. This data

TABLE 4-1. PROPERTIES OF ^{222}Rn

Property	Value
Volume of 27.03 pCi of ^{222}Rn at NTP ^a	$1.6 \times 10^{-20} \text{ m}^3$
Boiling point	-61.8°C
Melting point	-71°C
Vapor pressure at	
-144.0°C	0.13 kPa
-126.3°C	1.3 kPa
-111.3°C	5.3 kPa
-99.0°C	13 kPa
-71.0°C	53 kPa
-61.8°C	100 kPa
Density at NTP	9.96 kg m^{-3}
Coefficients of solubility ^b at atmospheric pressure:	
in water at	
0°C	0.507
10°C	0.340
20°C	0.250
30°C	0.195
37°C	0.167
50°C	0.138
75°C	0.114
100°C	0.106
in:	
glycerine	at 18°C at 0°C
aniline	0.21 -
absolute alcohol	3.80 4.45
acetone	6.17 8.28
ethyl acetate	6.30 7.99
petroleum (liquid paraffin)	7.35 9.41
xylene	9.20 12.6
benzene	12.75 -
toluene	12.82 -
chloroform	13.24 18.4
ether	15.08 20.5
hexane	15.08 20.09
carbon bisulfide	16.56 23.4
olive oil	23.14 33.4
	29.00 -

^aNTP - Normal Temperature and Pressure

^bThe solubility coefficient or partition coefficient in water is defined as the ratio C_w/C_a , where C_w and C_a are the radon concentrations in water and air, respectively.

Source: (UN82)

indicates that as the water temperature rises, the percentage of radon gas in the water decreases, while the percentage of radon in air increases. Thus, household activities that use warm or hot water will outgas more radon than activities that use cold water.

4.2 RADON DECAY AND PROGENY

Radon (^{222}Rn , half-life - 3.8 days) is produced by the decay of ^{226}Ra in the uranium series. Radon decays by alpha particle emission to ^{218}Po (half-life - 3 minutes), which decays by alpha particle emission to ^{214}Pb (half-life - 27 minutes), which then undergoes beta particle decay to ^{214}Bi (half-life - 20 minutes), which in turn decays by beta particle emission to ^{214}Po (half-life - 0.0002 seconds), which subsequently undergoes alpha particle decay to form the long-lived lead isotope, ^{210}Pb . ^{210}Pb has a half-life of 21 years and a relatively low beta-activity emission rate.

The atoms of radioisotopes that arise from the decay of ^{222}Rn atoms are called "radon progeny" or sometimes "radon daughters." It is important to note that radon progeny are solid atoms that can attach themselves to aerosols and in turn to surfaces they come in contact with such as walls, furniture (and in reference to health implications), human lungs.

The series of subsequent radioactive decays that each atom of ^{222}Rn undergoes along with the half-lives of ^{222}Rn and its progeny are illustrated in Figure 4-1. Table 4-2 lists the ^{238}U decay series along with historical names, half-lives, and major radiation energies and intensities (We82, UN82).

In order to better understand the relationship between radon and radon progeny, it is important to define the term radioactive equilibrium. Radioactive equilibrium is the state which prevails when the ratios between the amounts of successive members of the

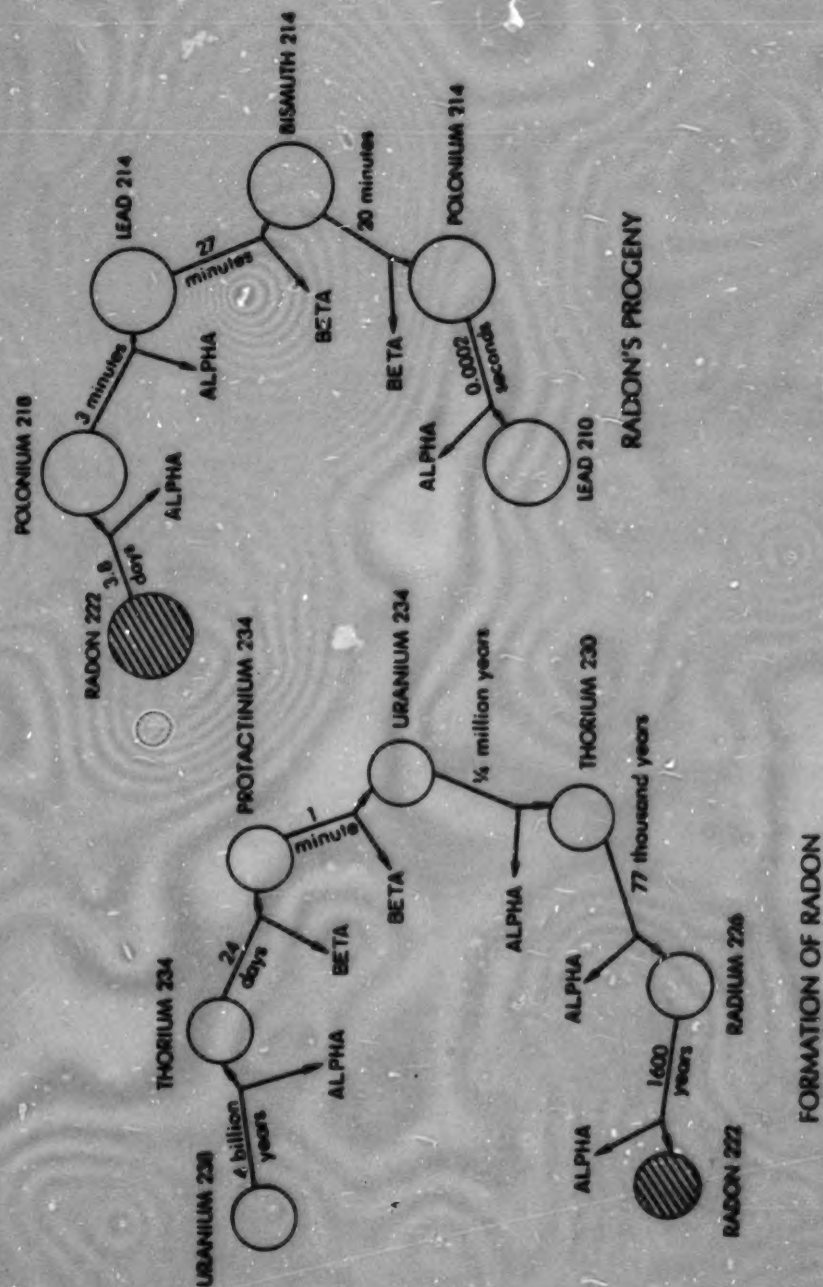


Figure 4-1
RADIOACTIVE DECAY CHAINS
FOR URANIUM AND RADON

Source LWRC-83

TABLE 4-2
Uranium Series ($4n + 2$)^a

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Nuclide	Historical name	Half-life	Major radiation energies (MeV) and intensities ^b		
			α	β	γ
$^{238}_{92}\text{U}$	Uranium I	$4.51 \times 10^9 \text{ y}$	4.15 (25%) 4.20 (75%)	---	---
$^{234}_{90}\text{Th}$	Uranium X ₁	24.1d	---	0.103 (21%) 0.193 (79%)	0.063 ^c (3.5%) 0.093 ^c (4%)
$^{234}_{91}\text{Pa}^a$	Uranium X ₂	1.17m	---	2.29 (98%)	0.765 (0.30%) 1.001 (0.60%)
$^{234}_{92}\text{U}$	Uranium I	6.75h	---	0.53 (66%) 1.13 (13%)	0.100 (50%) 0.70 (24%) 0.90 (70%)
$^{234}_{92}\text{U}$	Uranium II	$2.47 \times 10^5 \text{ y}$	4.72 (28%) 4.77 (72%)	---	0.053 (0.2%)
$^{230}_{90}\text{Th}$	Thorium	$8.0 \times 10^4 \text{ y}$	4.62 (24%) 4.68 (76%)	---	0.068 (0.6%) 0.142 (0.07%)
$^{226}_{88}\text{Ra}$	Radium	1602y	4.60 (6%) 4.78 (95%)	---	0.186 (4%)
$^{222}_{86}\text{Rn}$	Emanation Radon (Rn)	3.823d	5.49 (100%)	---	0.510 (0.07%)
$^{218}_{84}\text{Po}$	Radium A	3.05m	6.00 (~100%)	0.33 (~0.019%)	---
$^{218}_{82}\text{Pb}$	Radium B	26.8m	---	0.63 (50%) 0.71 (40%) 0.98 (6%)	0.293 (19%) 0.352 (36%)
$^{218}_{85}\text{At}$	Astatine	~2s	6.63 (6%) 6.70 (94%)	? (~0.1%)	---
$^{214}_{82}\text{Pb}$	Radium C	19.7m	3.45 (0.012%) 3.51 (0.008%)	1.0 (23%) 1.51 (40%) 3.26 (19%)	0.609 (47%) 1.120 (17%) 1.764 (17%)
$^{214}_{84}\text{Po}$	Radium C'	164 μ s	7.69 (100%)	---	0.799 (0.014%)
$^{214}_{83}\text{Bi}$	Radium C''	1.3m	---	1.3 (25%) 1.9 (36%) 2.3 (19%)	0.296 (80%) 0.795 (100%) 1.31 (21%)
$^{214}_{82}\text{Pb}$	Radium D	21y	3.72 (.000002%)	0.016 (85%) 0.061 (15%)	0.047 (4%)
$^{214}_{83}\text{Bi}$	Radium E	5.01d	4.63 (.00007%) 4.69 (.00005%)	1.161 (~100%)	---
$^{214}_{84}\text{Po}$	Radium F	138.4d	5.305 (100%)	---	0.803 (0.0011%)
$^{214}_{83}\text{Bi}$	Radium E''	4.19m	---	1.571 (100%)	---
$^{210}_{82}\text{Pb}$	Radium G	Stable	---	---	---

^aThis expression describes the mass number of any number in this series, where n is an integer.
Example: $^{238}_{92}\text{Pb}$ ($4n + 2$)..... $4(51) + 2 = 206$

^bIntensities refer to percentage of disintegrations of the nuclide itself, not to original parent of series.

^cComplex energy peak which would be incompletely resolved by instruments of moderately low resolving power such as scintillators.

Data taken from: Table of Isotopes and UNEP-78-001.

Source: (IHW70)

series remains constant (HEW70). Radon, because of its short half-life (3.8 days), is said to achieve transient equilibrium. If the half-life of the parent is short enough so the quantity present decreases appreciably during the period under consideration, but is still longer than that of successive members of the series, a stage of transient equilibrium will be reached after which all members of the series decrease in amount exponentially with the period of the parent. An example of this is ^{222}Rn and successive members of the series to ^{210}Pb (HEW70).

Some excellent work has been done by the Mine Safety and Health Administration (MSHA79) to characterize radon daughter growth with a constant radon source under various ventilation rates. The work was performed to simulate conditions in uranium mines but useful information can be applied to household situations. The results of the study are shown in Figures 4-2 through 4-12 which illustrate the ^{222}Rn daughter growth for the conditions listed on each figure.

The ^{222}Rn daughter growth is expressed in the occupational standard called a Working Level (WL). WL is defined as any combination of short-lived ^{222}Rn daughters through ^{214}Po in a liter of air which will result in the ultimate emission of 1.3×10^5 million electron volts (MeV) of potential alpha energy. The numerical value of the WL is derived from the alpha energy released by the total decay of the short-lived radon daughter products in equilibrium with 100 pCi/l of ^{222}Rn in air (Ku79). Figures 4-2 through 4-12 give the WL contribution from Ra A (^{218}Po), Ra B (^{214}Pb), and Ra C (^{214}Bi) and the total working level for each 100 pCi of radon per liter of air. The assumption is that none of the daughters are removed by plateout or filtration. The contribution of Ra C' (^{214}Po) is not given as it is negligible. The information in these figures are summarized in Tables 4-3 and 4-4.

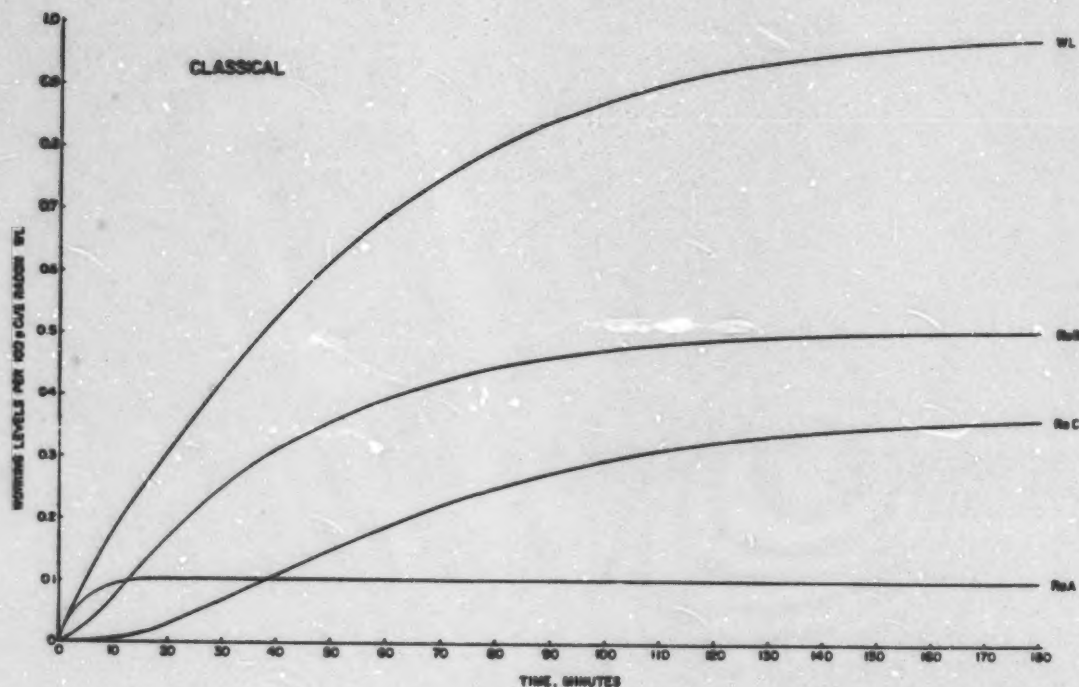


Figure 4-2 - Growth of working levels, classical.

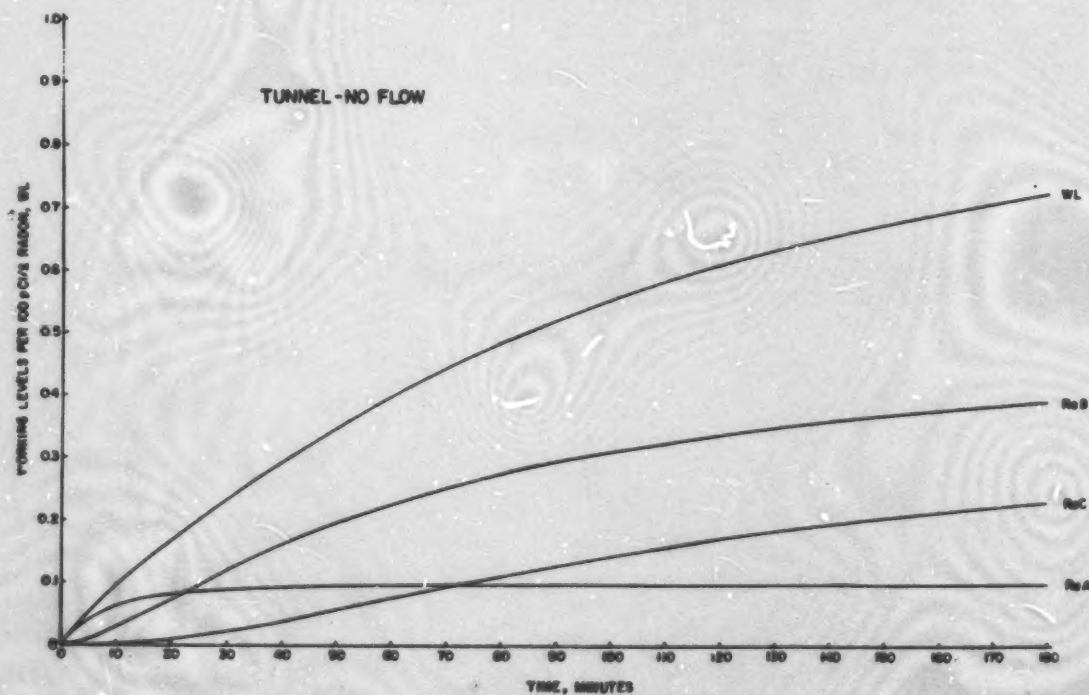


Figure 4-3 - Growth of working levels, tunnel situation, no flow.

Source: (MSHA 79)

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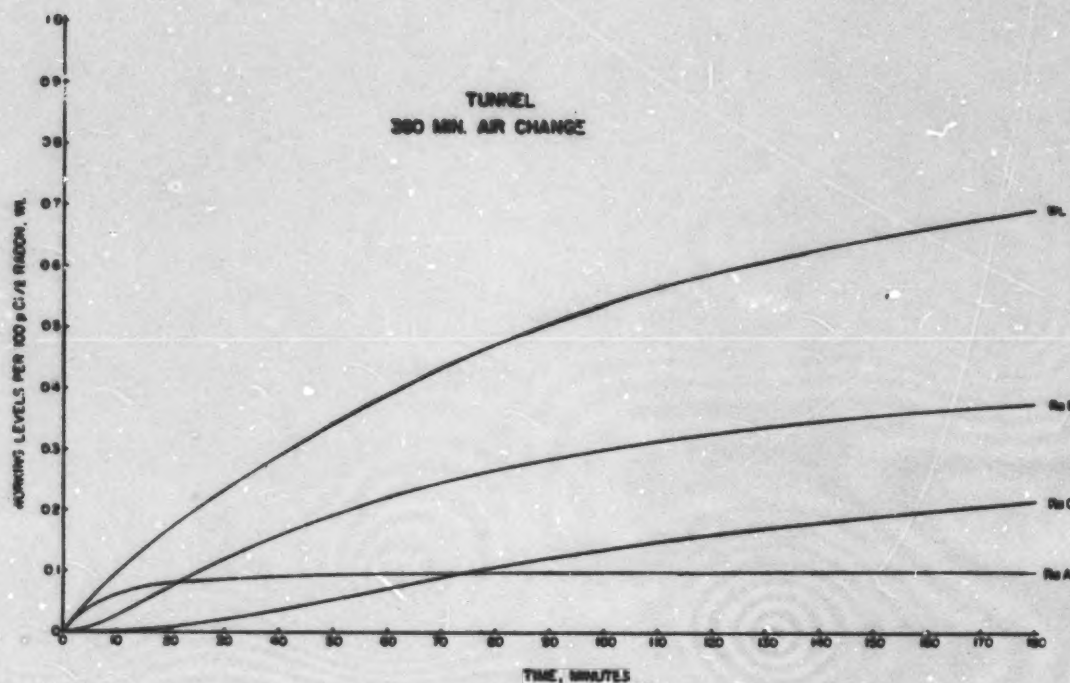


Figure 4-4 - Growth of working levels, tunnel situation, 360-minute air change.

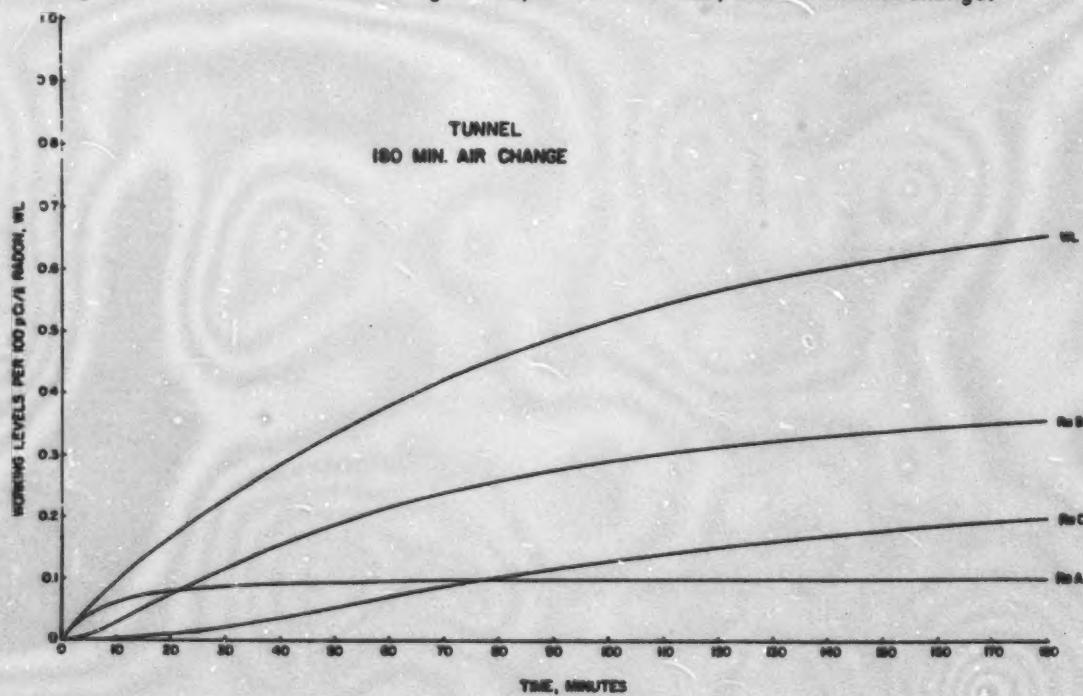


Figure 4-5 - Growth of working levels, tunnel situation, 180-minute air change.

Source: (MSHA 79)

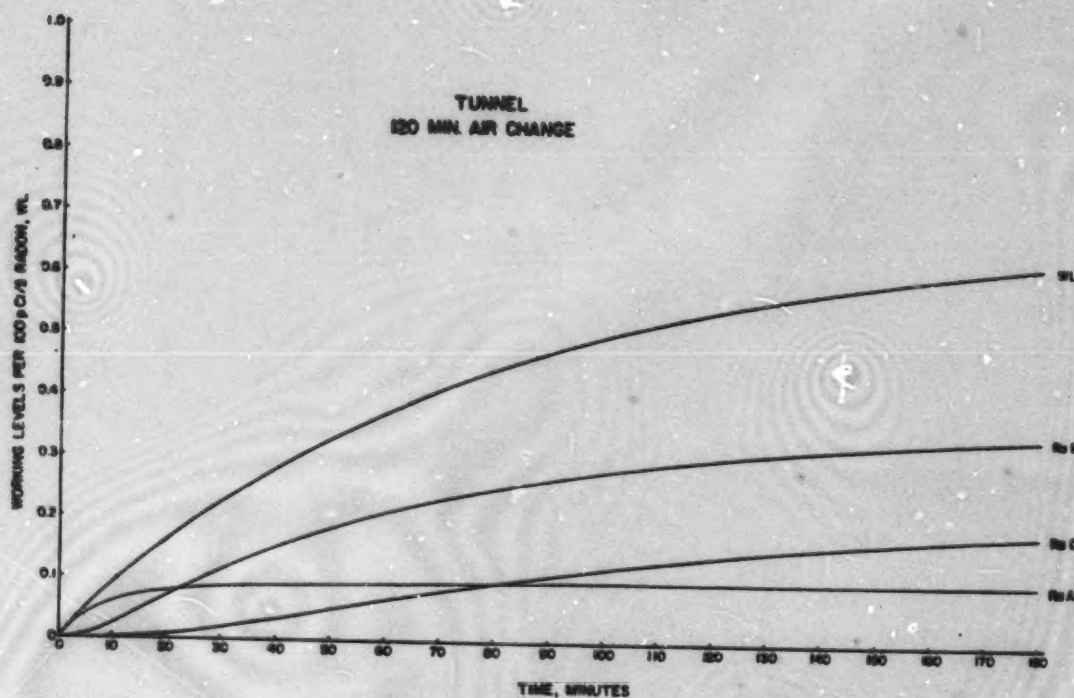


Figure 4-6 - Growth of working levels, tunnel situation, 120-minute air change.

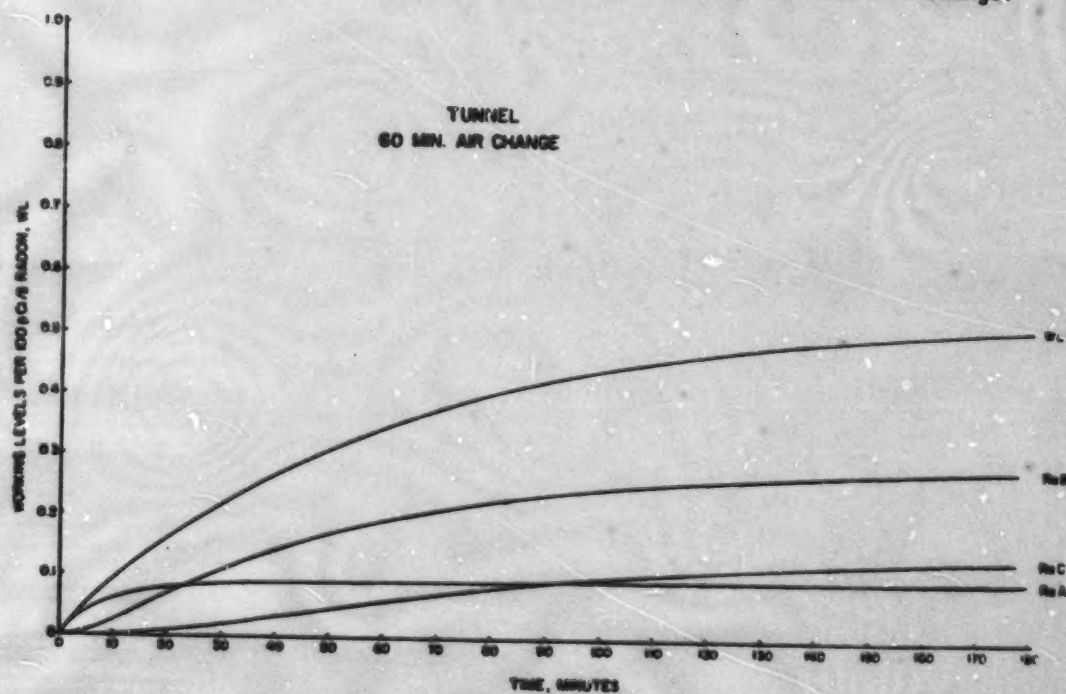


Figure 4-7 - Growth of working levels, tunnel situation, 60-minute air change.

Source: (MSHA 79)

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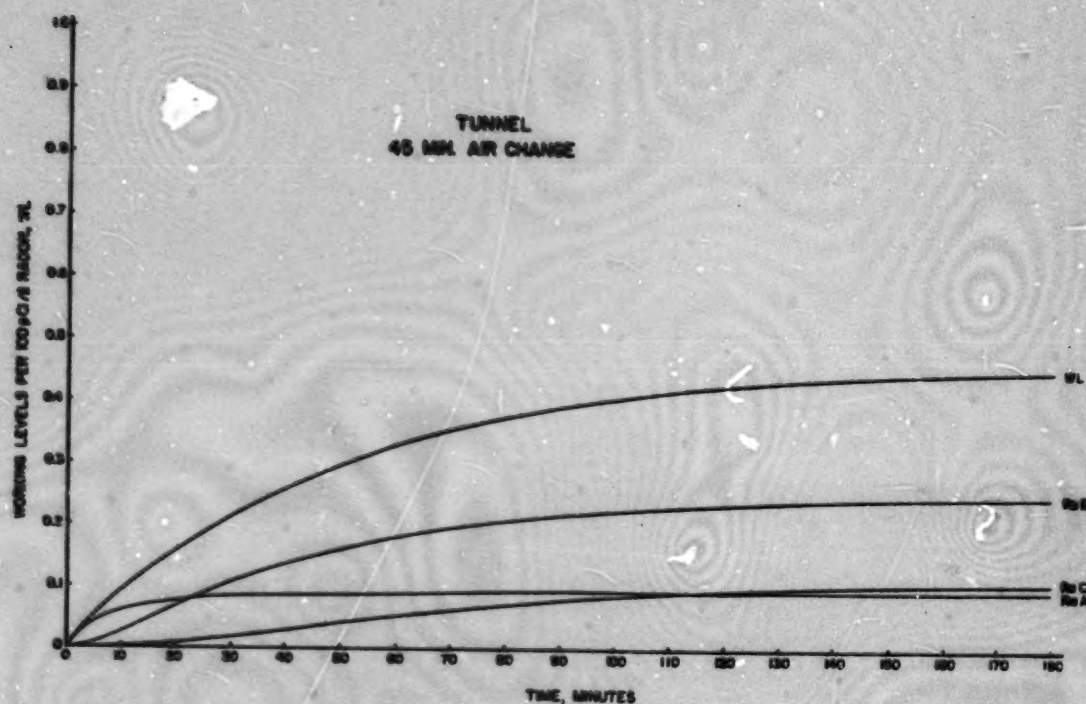


Figure 4-8. - Growth of working levels, tunnel situation, 45-minute air change.

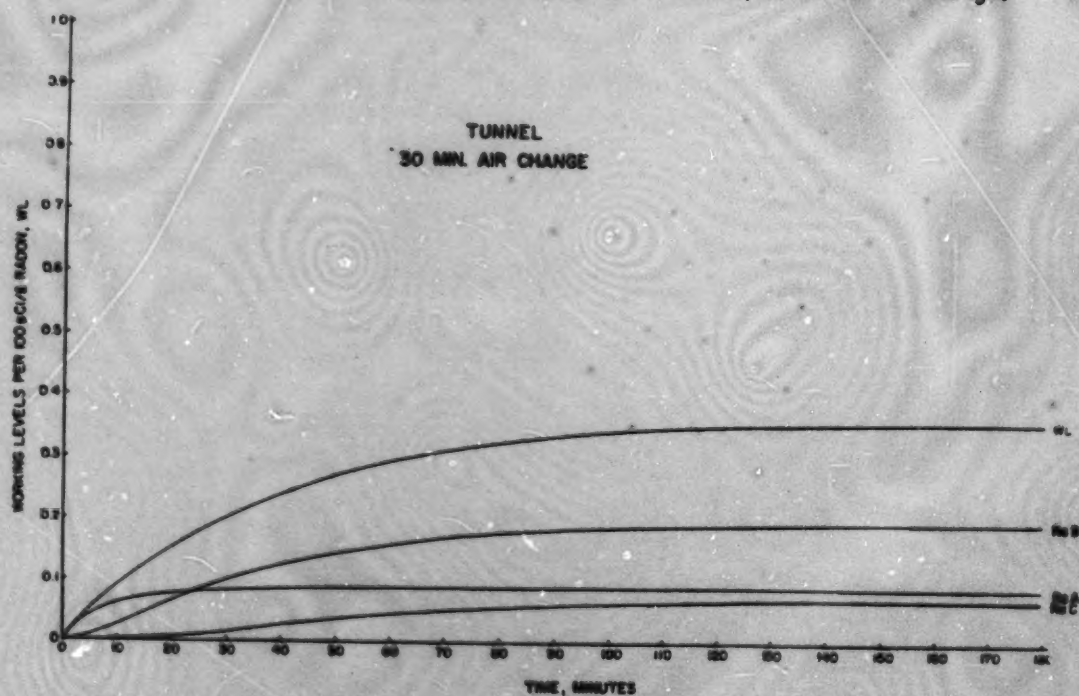


Figure 4-9 - Growth of working levels, tunnel situation, 30-minute air change.

Source: (MSHA 79)

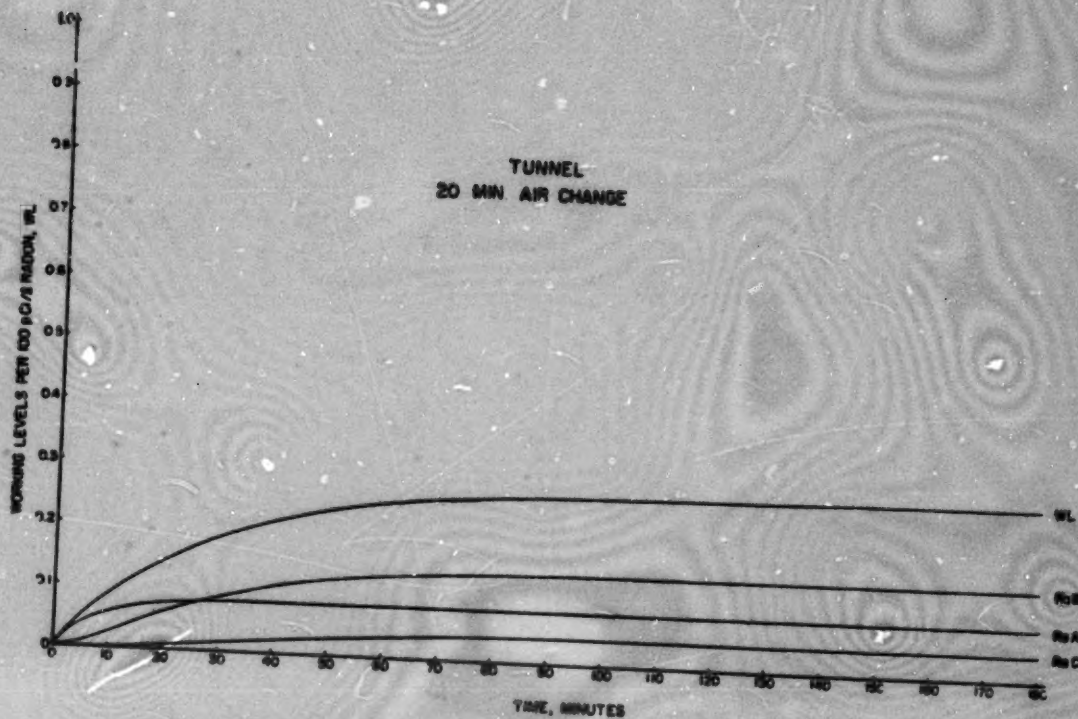


Figure 4-10 - Growth of working levels, tunnel situation, 20-minute air change.

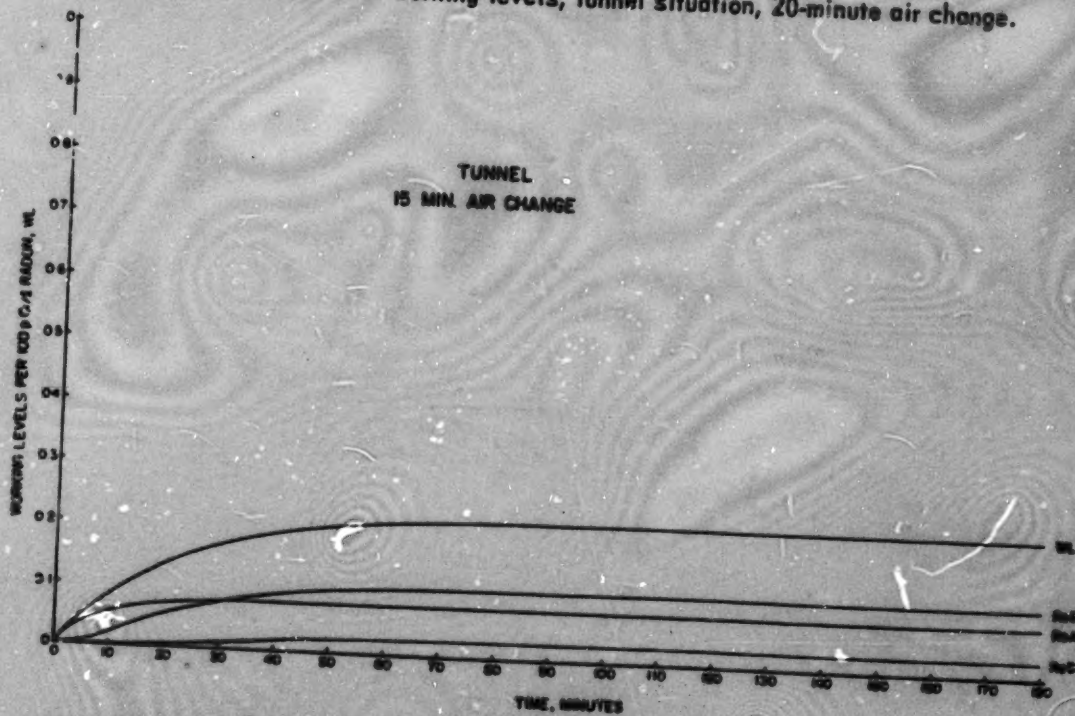


Figure 4-11 - Growth of working levels, tunnel situation, 15-minute air change.

Source: (MSHA 79)

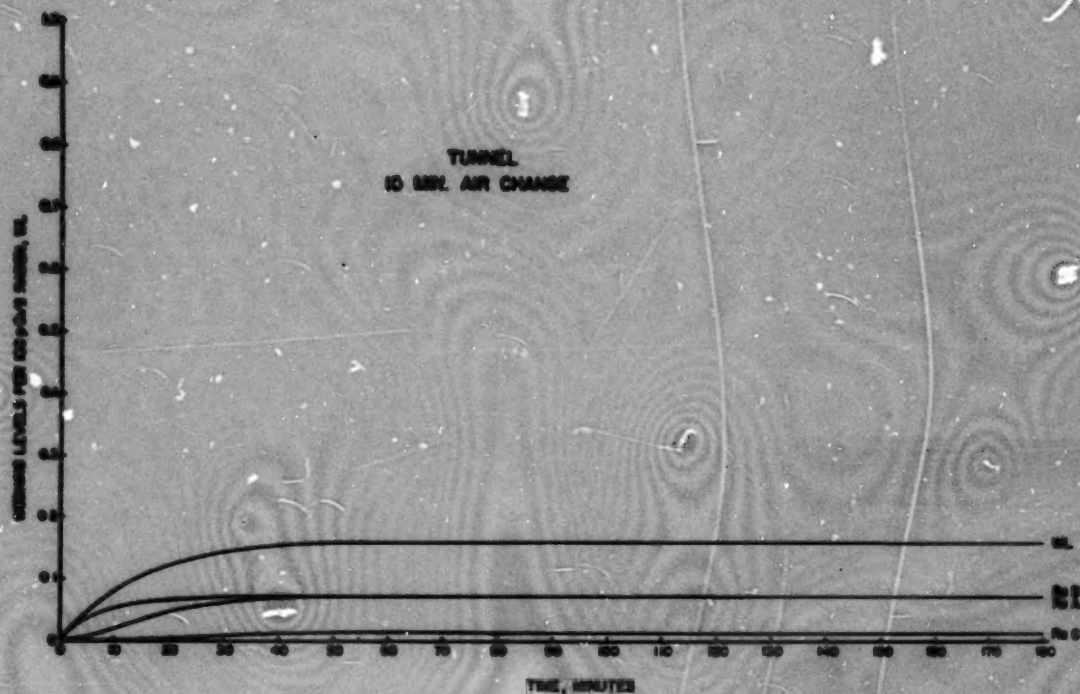


Figure 4-12 - Growth of working levels, tunnel situation, 10-minute air change.

Table 4-3 - Radon-daughter growth curve comparison

Figure	Description	Time for one air change, min	Total radon-daughter concentration at various times. WL per 100 pCi/l. min					
			10	20	30	60	120	180
1	Classical..	(¹)	0.175	0.306	0.423	0.687	0.920	0.981
2	Tunnel.....	(¹)	.095	.167	.233	.399	.614	.730
3	...do.....	360	.094	.166	.231	.390	.589	.693
4	...do.....	180	.094	.165	.229	.381	.564	.655
5	...do.....	120	.093	.163	.226	.372	.540	.618
6	...do.....	60	.092	.160	.217	.344	.468	.513
7	...do.....	45	.091	.157	.212	.327	.426	.452
8	...do.....	30	.090	.152	.200	.292	.352	.361
9	...do.....	20	.088	.144	.184	.247	.273	.275
10	...do.....	15	.085	.136	.169	.211	.221	.221
11	...do.....	10	.081	.121	.142	.159	.161	.161

¹ No flow.

Source: (MSHA 79)

Table 4-4 - Individual daughter growth

Figure	Description	Time for one air change, min	Radon Daughter Concentrations (Ra A, Ra B, Ra C) (pCi/100 pCi radon)				
			Elapsed Time in Minutes				
			10	20	30	60	120
1	Classical...	(a)	90,14,2	99,33,9	100,48,18	100,76,50	100,93,86
2	Tunnel.....	(a)	64,6,1	78,15,3	85,23,6	93,44,20	96,66,46
3	...do.....	360	60,6,1	78,14,3	85,23,6	92,43,19	96,63,43
4	...do.....	180	60,6,1	77,14,3	85,23,6	91,41,19	95,61,40
5	...do.....	120	60,6,0	77,14,3	85,22,6	91,40,18	94,58,37
6	...do.....	60	59,5,0	76,14,2	83,21,5	89,37,16	92,50,30
7	...do.....	45	59,5,0	75,13,2	82,21,5	88,35,14	90,46,25
8	...do.....	30	58,5,0	74,13,2	80,19,5	85,30,12	87,37,18
9	...do.....	20	57,5,0	72,12,2	77,17,4	81,25,9	82,28,11
10	...do.....	15	56,5,0	69,11,2	74,15,3	77,21,6	77,22,7
11	...do.....	10	54,4,0	65,9,1	68,12,2	69,14,4	69,14,4

a No flow.

b For a full explanation of the data presented in this table, the reader is encouraged to refer to Reference MSHA79.

3
As expected, the radon daughter concentration at any specific time is lower when the ventilation airflow is greater. In fact, for the non-zero flow rates with a constant radon source, a steady-state condition is achieved. For instance, for the 20-minute airchange curve, the radon daughter concentration does not increase after 180 minutes; for the 15-minute curve, 100 minutes; and for the 10-minute curve, 80 minutes.

This information can be used to estimate the concentrations of radon progeny in a house assuming no plateout and no loss to filtration. If a house has a steady-state radon level of 10 pCi/l and an airchange rate of 1 hr⁻¹, then the radon progeny levels can be calculated as follows. From Table 4-4, after 180 minutes, the radon and progeny can be found in the ratio of 1.0, 0.93, 0.55, 0.35 for radon, Ra A, Ra B, and Ra C, respectively. Thus, the radon progeny can be computed to be 9.3, 5.5 and 3.5 pCi/l for Ra A, Ra B, and Ra C, respectively, and have a WL of approximately 0.05.

The health effects of radon can be described as follows. Because radon is essentially chemically inert, radon that is inhaled is also exhaled (LWRC83). The radon progeny, however, are chemically active, being metals, such as lead, bismuth, and polonium. These elements are charged atoms that adhere to surfaces with which they come into contact, such as particulates in the air and furniture and room surfaces. When inhaled, approximately 30 percent of the radon progeny, both attached to particulates and free, come into contact with air passageways in the lungs and adhere to the surfaces. Radiation from such radon progeny can strike and break molecules in living cells (LWRC83).

The health risks of radon and radon progeny are mainly due to the emission of alpha particles from ²¹⁸Po and ²¹⁴Po. This is due to the nature of an alpha particle itself. An alpha particle is a helium atom moving at high speed. Alpha particles lose speed as

they pass through matter and knock electrons off molecules of such matter. This process is called "ionization." Internally, alpha radiation is believed to be ten times more harmful than beta and gamma radiation because of the mass differential (LWRC83). Thus, the major health effect of radon is due to alpha radiation associated with the radon progeny ^{218}Po and ^{214}Po . This fact must be kept in mind when evaluating alternative treatment technology for radon and radon progeny removal from household air.

4.3 EXISTING REGULATIONS AND GUIDELINES

Recognition that radon and its daughter products, released into homes from building materials, soils, water and natural gas by outgassing, can be a problem in many houses is comparatively recent in the United States. There are no national standards for maximum allowable levels in the residential environment, nor are there standards for building materials. There are standards for occupational exposure, developed to protect the health of uranium miners and, in a few isolated instances, guidelines have been established for the instigation of remedial action for houses built on inactive uranium processing sites or phosphate mine tailings. Occupational exposure guidelines are generally less stringent than those which would be specified in a residence, but they provide a starting point for projections as to what levels should be acceptable in the living environment on a 24-hour per day basis.

In 1964, the International Commission on Radiological Protection (ICRP) presented a formula for estimating the Maximum Permissible Concentration (MPC) of radon based on the fraction of the equilibrium amount of Ra A which, if the fraction equals 10 percent, results in a MPC in air of 30 pCi/l (occupational exposure). However, both the ICRP and National Council on Radiation Protection and Measurement (NCRP) recommend that individuals in the general public be exposed only to levels limited to one-tenth of the recommended MPCs for occupational personnel. Dr. J. A. Auxier,

the Director of Oak Ridge National Laboratory, Health Physics Division, and the Swedish National Institute for Radiation Safety generally concur. Thus, Kusuda (Ku79) concluded that if a criterion is to be applied today, the MPC for radon in homes should not exceed the suggested 3 pCi/l which is consistent with AEC regulations of 1966, as amended. The Swedish National Institute for Radiation Safety estimates that a 1 pCi/l limit of radon corresponds to a cancer risk of 20 persons per million. [This projection is based on data obtained at higher levels of exposure (Ku79)].

A summary of existing regulations as well as various authors suggested guidelines are summarized in Tables 4-5 and 4-6 for airborne and waterborne radon along with any key assumptions.

4.4 SOURCES AND SOURCE STRENGTHS OF RADON ENTERING HOMES

This section of the report briefly describes sources of radon in buildings and summarizes available literature information on these sources. The primary sources of radon in buildings are the soil adjacent to the foundation, construction materials such as concrete, and potable water supplies. Secondary sources include home heating fuels and background radon in ambient air.

4.4.1 Soil, Rock, Home Subsurface

Available information about the emanation rate of ^{222}Rn from soil, rock and other home subsurface materials is summarized in Tables 4-7 and 4-8. The literature reviewed indicates that a typical range of emanation rates from subsurface materials is 0.005 to 1.9 pCi/m²-sec with a mean value of 0.42 pCi/m²-sec.

Table 4-9 lists radium activity concentrations and radon exhalation rates from several types of rocks and various uranium minerals.

TABLE 4-5. ^{222}Rn AND PROGENY AIRBORNE STANDARDS OR RECOMMENDED GUIDELINES

Current Source	Original Source	Standard or Recommended Guideline	Basis or Key Assumptions
He83	EPA80, EPA80a	0.015 WL	Houses built on inactive uranium processing sites
He83	EPA79	0.02 WL	Houses built on phosphate mine tailings in Florida
He83	AEC77	0.15 WL; prompt remedial action 0.02 WL; remedial action	For homes built on uranium mine wastes; Atomic Energy Control Board of Canada
He83	SMA79	0.054 WL; for existing buildings (after remedial action) 0.019 WL; for new buildings	Sweden
Ge83		3 pCi/l ^{222}Rn	NRC limit
Ge80		3 pCi/l ^{222}Rn	International Commission on Radiological Protection (1959) U.S. Surgeon General, 0.01 WL equal to about 2 pCi/l under normal circumstances (1970).
He82		3 WL months/year; 0.25 WL exposure rate for 12 months at 170 working hours/month	Current standard for uranium miners
He82	US Government	0.05 WL - remedial action 0.01-0.05 - action suggested	U.S. for homes built on uranium mine tailings - U.S. Surgeon General's Guidelines (1972)
He82	USEPA 1980	3 pCi ^{222}Rn /liter air - remedial action	For houses built on inactive Uranium Processing Sites
He82	Akerblom & Wilson 1981	1.9 pCi/l ^{222}Rn - new dwellings 5.4 pCi/l ^{222}Rn - rebuilt dwellings 10.8 pCi/l ^{222}Rn - existing dwellings	Criteria in Sweden
Ku79	Fed. Reg., Vol. 33, No. 252, 1968	2 WL months in consecutive 3 month period 4 WL months in any consecutive 12 month period	Secretary of Labor (1968) for mining industry
Ku79	Fed. Reg., Vol. 34, No. 11, 1968	1-2 WL; immediate corrective action must be taken	For mining industry Department of the Interior (1968)

TABLE 4-6. ^{222}Rn WATERBORNE STANDARDS OR RECOMMENDED GUIDELINES

Current Source	Original Source	Standard or Recommended Guideline	Basis or Key Assumptions
Me81	NBS Handbook 52, 1953	2,000 pCi/l ^{222}Rn	
Me81	NBS Handbook 69, 1959	Radon in water eliminated pending more thorough detailed studies and development of a firmer data base	
Me81	Am69, Be61, Hu65, vDo64, He66	1,800-100,000 pCi/l ^{222}Rn	
Me81	Hox66	3,000 pCi/l ^{222}Rn	
Me81	He66, Su72	20,000 pCi/l ^{222}Rn 100,000 pCi/l ^{222}Rn	Large populations occupational workers
Hi79	USEPA	No standard for radon in water	ICRP and NCRP
		500 pCi/l ^{222}Rn	Radiological Quality of the Environment in the United States, 1977
	Hi79	10,000 pCi/l ^{222}Rn	Recommended by Hickey

TABLE 4-7. ^{222}Rn SOIL EMANATION RATES

Current Source	Original Source	Emanation Rate	Basis or Key Assumptions
UN77		Range 6×10^{-3} to $1.4 \text{ pCi/m}^2\text{-s}$ Mean value - $0.42 \text{ pCi/m}^2\text{-s}$ World-wide emanation rate from land - 50 Ci/s Contribution from ocean - 0.5 to 5.0 Ci/s	Based on 1,000 measurements
NRC91		Mean Emanation Rate ^{222}Rn - $0.42 \text{ pCi/m}^2\text{-s}$ Contribution from soil gases - $100\text{--}2,000 \text{ pCi/l}$	
Me74		Radon Emanation Rate - $2.7 \times 10^{-18} \text{ Ci/s-g}$	
UN77 (Annex D)		Radon - area weighted exhalation rate (excluding Antarctica and Greenland's ice caps) - $0.43 \text{ pCi/m}^2\text{-s}$ Other estimates - $0.41 \text{ pCi/m}^2\text{-s}$ $0.51 \text{ pCi/m}^2\text{-s}$ Reported ranges - 0.005 - $1.9 \text{ pCi/m}^2\text{-s}$	Value for soil originating from the weathering of granite rock
	Is62 B171		
	Ge80 W175		

TABLE 4-8. PUBLISHED VALUES OF ^{222}Rn EXHALATION RATES/UNIT AREA

Location	Soil Group	Radon Exhalation Rate per Unit Area ($\mu\text{Ci}/\text{m}^2\cdot\text{s}$)	Original Source ^b
Austria:			
Gras	Mountain	0.54, 0.24	K21
Innsbruck	Mountain	0.23	Z1
Innsbruck	Mountain	0.51	Z2
France: Saclay (80) ^a	Podsollic	0.41, 0.38	S50
Germany, Fed. Rep.: Aachen	Podsollic	0.46	I12
Ireland: Dublin	Podsollic	0.73	S51
Japan: Osaka (4.4)	Latosollic	0.09, 0.24	M24
Philippines: Manila	Latosollic	0.30	W18
United States:			
Socorro, NM (10)	Desertic	0.92±0.09	W19
Socorro, NM (6)	Desertic	1.03±0.30	P16
Yucca Flat, NV	Desertic	0.49	K17
Lincoln, MA (10)	Podsollic	1.35	K17
Champaign County, IL (472)	Chernozemic	1.43	P16
Argonne, IL (8)	Chernozemic	0.57±0.05	P16
USSR:			
Kirov (36)	Podsollic	0.41	M25
Moscow (6)	Podsollic	0.10	M25
Central European Territory (40)	Podsollic	0.19	S52
Southwest Kazakhstan (5)	Desertic	0.14	S52
Sandy Desert (Muyun Kum, Ashkhabad, Dzhusaly) (10, 5)	Desertic	0.13, 0.35	K22
The North (Murmanak, Arkhangelsk) (6)	Podsollic	0.10	K22
Central European Territory (35)	Podsollic	0.20	K22
Leningrad, Moscow, Kaluga reg.	Chernozemic		
The Caucasus (15)	Mountain	0.30	K22
Grozny, Baku, Tbilisi, Adler	Chernozemic		
Middle Asia (10)	Mountain	0.51	K22
Tashkent, Alma-Ata, Frunze	Desertic		
South Urals (5)	Mountain	0.30	K22
Sverdlovsk	Podsollic		
Chelyabinsk	Mountain	0.30	K22

^aNumber of analyses on which exhalation rate is based.^bThese original sources are as they appeared in the cited current source. The current source's bibliography contain these references.

Source: (UN77)

TABLE 4-9. ^{222}Rn EXHALATION FROM ROCK AND URANIUM MINERALS

<u>Type of Rock</u>	<u>Radium Activity Concentration (pCi/g)</u>	<u>Radon Exhalation Rate for Cores (pCi/m²-s)</u>
Leptite ^a	2.1	0.01
Aptite (1)	12.4	0.03
Aptite (2)	7.6	0.02
Pegmatite (1)	9.2	0.14
Pegmatite (2)	8.9	0.22
Uranium Minerals:		
Sample 1	2,973.3	7.03
Sample 2	8,379.3	21.08
Sample 3	2,189.4	4.60
Sample 4	1,946.2	1.70
Sample 5	121,635	5.14
Sample 6	6,487.2	0.21
Sample 7	756.8	0.27

^aRadon exhalation rate from a gallery surface was 0.20 pCi/m²-s.

Source: (UN77)

A computation of the radon contribution to indoor air from soil, rocks and home surfaces for various emanation rates follows.

Basis: $V_{\text{house}} = 230,000$ liters
 ceiling height = 2.5 m
 floor area = 92 m²
 $\lambda = 1$ hr⁻¹
 E = emanation rate (pCi/m²-sec)
 C_a = concentration of radon in air
 attributable to soil, etc. (pCi/l)

$$(E \text{ pCi/m}^2\text{-sec})(3600 \text{ sec/hr})(\text{hr}/230,000 \text{ liters})(92 \text{ m}^2) = C_a$$

$$(E \text{ pCi/m}^2\text{-sec})(1.44) = C_a \text{ pCi/l}$$

<u>Emanation Rate</u> <u>(pCi/m²-sec)</u>	<u>C_a</u> <u>(pCi/l)</u>
0.005	0.007
0.42	0.605
1.9	2.74

Thus, depending on the soil, rock or home subsurface emanation rate, the radon contribution to the house air could range anywhere from 0.007 to 2.74 pCi/l with a typical contribution being 0.6 pCi/l.

4.4.2 Building Construction Materials

This section summarizes available information about the emanation rate of ²²²Rn from building construction materials. There are five major factors that affect the emanation of radon from building materials: 1) the ²²⁶Ra content of the building material, 2) moisture content of the material, 3) type of surface coating, 4) ventilation rate, and 5) thickness of the building material.

The ^{226}Ra content of the building materials serves as a constant source of radon gas. This can be explained by the fact that ^{226}Ra decays by alpha particle emission to ^{222}Rn . The half-life of ^{226}Ra is 1600 years so that secular equilibrium is established between radium and radon. Thus, a building material with a fixed radium content generates a constant supply of radon gas. The other four major factors, moisture content, surface coating, ventilation rate, and thickness of the building material, all affect the rate of mass transfer of radon gas from within the building material to the indoor air.

As a rule of thumb, the fractional escape (pCi escaped per pCi produced) of ^{222}Rn is on the order of 1 percent from building materials in walls and ceilings (UN77). However, considerably higher escape rates (8-25%) have been reported, particularly for concrete (NRC81). The escape, or exhalation, rate has been shown to be dependent not only on the type of building materials, but also wall thickness, coatings, or coverings used, and environmental conditions (pressure, temperature and moisture) (NRC81, Ei80, Ab83). Table 4-10 shows the estimated emanation rate per unit concentration of ^{226}Ra from different materials. Tables 4-11 through 4-15 give the activity concentration of naturally occurring isotopes, including ^{226}Ra which is a source of ^{222}Rn , for various building materials. Table 4-16 gives the exhalation rate of ^{222}Rn from different building materials.

The following example will help explain the use of these tables and provide an estimate of the possible radon contribution from building materials to indoor air.

Basis: $V_{\text{house}} = 230,000$ liters
 ceiling height = 2.5 m
 floor area = 92 m²
 $\lambda = 1$ airchange/hour
 U.S. home

TABLE 4-10

RADON EMANATION RATES
OF VARIOUS MATERIALS

<u>Material</u>	<u>Emanation rate of ^{222}Rn per unit activity concentration of ^{226}Ra ($\text{pCi m}^{-2}\text{s}^{-1}$ per pCi g^{-1})</u>	<u>Comments</u>	<u>Reference^a</u>
By-product gypsum	0.01	Internal walls 76 mm thick	265
By-product gypsum	0.001	Ceilings 13 mm thick	265
Concrete	0.005	10 cm thick	306
Uranium mill tailings	0.2	10 cm thick	306
Uranium mill tailings	1.6	"Infinite" thickness	306
Soil	0.5	"Infinite" thickness	33
Light concrete	0.02	20 cm thick	195
Heavy concrete	0.01	8 cm thick	195

^aThese original sources are as they appeared in the cited current source. The current source's bibliography contain these references.

SOURCE: (UN77)

TABLE 4-11

ACTIVITY CONCENTRATION OF NATURALLY
OCCURRING RADIONUCLIDES IN BUILDING
MATERIALS EXPECTED TO GIVE RISE TO
HIGHER-THAN-AVERAGE EXTERNAL ABSORBED DOSES

Type of Building Material	Country	Number of Samples	Average Activity Concentration ($\mu\text{Ci g}^{-1}$)			Reference ^b
			⁴⁰ K	²²⁶ Ra	²³² Th	
Granite	FRG	34	33	2.6	2.2	327
Granite bricks	UK	7	28	2.4	2.3	117
Granite	USSR	2	40	3.0	4.5	194
Pumice stone	FRG	20	29	3.0	3.4	327
Concrete containing alum shale	Sweden	83	23	40.4	2.0	335
Phosphogypsum						
From apatite	FRG	2	<1	1.5	<0.5	327
From phosphorite	FRG	39	3	16	<0.4	327
Of unknown origin	FRG	7	2	<0.5	<0.7	327
Phosphogypsum	UK	6	2	21	0.5	117
Phosphogypsum	USA	-	-	40	0.2	105
Red-slime bricks	FRG	23	9	7.6	6.3	327
Fly ash	FRG	28	19	5.7	3.5	327
Fly ash ^a						
Type 1	UK	1	15	0.2	1.0	117
Type 2	UK	1	15	3.7	0.9	117
Type 3	UK	1	6	1.4	1.2	117
Blast-furnace slags	USSR	29	6.6	1.8	0.5	194

^aMixture of coal clinker, ash and cement.

^bThese original sources are as they appeared in the cited current source. The current source's bibliography contain these references.
Source: (UN77)

TABLE 4-12. RADIONUCLIDE CONTENT OF EXTERIOR WALL CONSTRUCTION MATERIALS

Exposure Rate Category	Number of Samples	Radionuclide (pCi/g)					
		226Ra Daughters ^a		232Th Daughters ^b		40K	
		Mean	Range	Mean	Range	Mean	Range
Brick:							
Very low	2	0.2	0.1-0.3	0.08	0.04-0.1	0.3	0.2-0.4
Low	5	0.6	0.6-0.7	0.9	0.8-1.0	12.0	11-13
Medium	24	1.8	1.0-3.4	1.9	1.1-3.0	17.0	10-28
High	6	3.5	2.8-4.8	2.9	2.4-3.9	27.0	21-32
Concrete:							
Low	3	0.7	0.5-1.1	0.5	0.4-0.6	8.0	7.1-9.8
Medium	3	1.3	1.0-1.6	1.6	1.3-1.9	26.0	18-31
High	1	2.4		3.2		27.0	
Concrete Block:							
Medium	8	1.3	1.1-1.6	1.7	1.2-2.2	26.0	24-31
Very High	2	21.0		1.0		8.6	7.7-9.4

^aConcentrations of individual samples were computed for 226Ra daughters by averaging five gamma-ray values for 214Pb and 214Bi.

^bConcentrations of individual samples were computed for 232Th daughters by averaging four gamma-ray values for 228Ac and 208Tl.

Source: (E180)

TABLE 4-13. RADIONUCLIDE CONTENT OF CONCRETE COMPONENTS

Exposure Rate Category	Number of Samples	226Ra Daughtersa				Radionuclide (pCi/g)			
		232Th Daughtersb		40K		232Th Daughtersb		40K	
		Mean	Range	Mean	Range	Mean	Range	Mean	Range
Coarse Aggregate									
Gravel:									
Very low	1	0.4		0.06		1.5			
Medium	5	0.9	0.6-1.5	1.2	1.0-1.7	22.0	15-30		
Expanded shale and clay:									
Medium	6	1.2	0.9-1.6	1.6	1.3-2.1	23.0	16-34		
High	4	2.1	1.9-2.3	3.4	2.9-4.0	25.0	22-29		
Fine Aggregate									
Sand:									
Low	5	0.3	0.1-0.6	0.4	0.2-0.6	3.2	1.1-5.6		
Rock dust:									
Low	1	0.4		0.4		8.8			
Medium	3	1.2	0.7-1.9	1.3	0.8-2.0	21.0	14-33		
Cement									
Cement:									
Low	6	1.0	0.5-1.4	0.3	0.2-0.6	2.1	0.7-2.9		
Fly Ash:									
Medium	2	3.4	3.3-3.5	2.4	2.0-2.8	8.2	3.3-13		
High	14	5.3	3.5-8.3	3.1	2.2-4.3	19.0	4-28		

^aConcentrations of individual samples were computed for ^{226}Ra daughters by averaging five gamma-ray values for ^{214}Pb and ^{214}Bi .

^bConcentrations of individual samples were computed for ^{232}Th daughters by averaging four gamma-ray values for ^{228}Ac and ^{208}Tl .

Source: (E180)

TABLE 4-14. MEAN ACTIVITY CONCENTRATIONS OF SOME BUILDING MATERIALS

Country	Material	No. ^a	Mean Activity Concentration (pCi/g)		RefC	Comments
			226Ra	232Th/ 228Th		
Germany, Fed. Rep.	Building sand and gravel	50	<0.41	<0.51	N2	Many sources
	Granite	32	2.70	2.19	N2	Different types
	Bricks (traditional constituents)	109	1.59	1.81	N2	Different types
	Pumice-aggregate concrete blocks	31	2.00	2.19	N2	Adequate sampling
	Slag-aggregate concrete blocks	9	4.11	2.70	N2	Depends on feed materials
	Portland cement	14	<0.70	<0.51	N2	Several sources
	Natural gypsum	23	<0.51	<0.30	N2	Many sources
	Chemical gypsum (phosphogypsum)	33	15.00	<0.51	N2	Depends on source of rock
	Red mud bricks	23	7.60	6.30	N2	Variable composition
	Fly ash	28	5.70	3.51	N2	Many sources
Hungary	Concrete	95	0.35	0.30	T7	Avg. weighted by relative prod.
	Brick	176	1.51	1.30	T7	Avg. weighted by relative prod.
Italy	Lithoid tuff (tufo litoide, Monte Cimino)	-	3.49	3.30	N2	Commonly used for house building
	Menfro (variety of tuff, Tuscania)	-	6.51	5.89	N2	Wall cladding material
Poland	Fly ash	106	1.7-16.5	0.9-8.6	P4	Typical building material used
	Slag	42	0.5-12.4	0.6-15.9	P4	in Poland.
	By-product gypsum	4	0.7-20.0	0.3-1.2	P4	
	Red brick	3	0.5-0.6	0.6-1.2	P4	
	Silicon brick	3	0.2-0.4	<0.1-0.2	P4	
	Cement	4	0.2-0.7	0.3-1.8	P4	
	Soil	5	0.1-0.5	<0.1-0.4	P4	
	Granites	7	2.41	2.19	H2	Inadequate sampling
	Sand and gravel	10	0.11	0.19	O2	Inadequate sampling
	Cement	6	0.59	0.49	O2	Inadequate sampling
United Kingdom	Clay bricks	25	1.41	1.19	H2	Sampling probably inadequate
	White bricks (autoclaved flint and quicklime)	5	0.11	0.14	H2	Aggregate may vary
	Natural gypsum	73	0.59	0.19	H2	Adequate sampling
	Lightweight blocks various aggre.	10	1.59	0.70	H2	Inadequate sampling
	Phosphogypsum from sedim. ores	60	17.00	0.49	O2	Depends on ore source
	Phosphate landfill, Florida	-	20.00	-	U2	Estimate depends on geological structure and reclamation procedures
	Gypsum from Florida phosphate rock	-	33.00	0.27	U3	Samples from several processing facilities
	Uranium mine tailings	-	125.01	-	Cl1	Personal assay of complex situation

^aNo. = Number of samples; ^bexceptional values; source's bibliography contain these references. Sources: (UN77)

TABLE 4-15. MEAN ACTIVITY CONCENTRATIONS OF SOME BUILDING MATERIALS IN NORDIC COUNTRIES

Building Materials	Country	No. ^a	²²⁶ Ra (pCi/g)			²³² Th (pCi/g)			Comments ^b	Ref ^c
			Min.	Avg.	Max.	Min.	Avg.	Max.		
Brick	Denmark	79	0.62	1.14	2.32	0.57	0.92	1.57	AS	U1
	Finland	37	1.00	2.16	3.62	1.00	1.68	2.46	AS	M21
	Norway	18		1.70			2.00			S41
	Sweden	12	1.11	2.59	4.11	2.70	3.43	4.81	IS	S42
Limestone Bricks	Denmark	5	0.16	0.22	0.30	0.11	0.19	0.30	AS	U1
	Finland	3	0.54	0.59	0.68	0.49	0.62	0.78	IS	M21
	Sweden	3	0.19	0.27	0.41	0.11	0.22	0.27	IS	S42
Concrete	Denmark	6	0.35	0.43	0.65	0.24	0.35	0.46	IS	U1
	Finland	12	1.35	1.65	2.16	0.76	1.00	1.14		M22
	Norway	137	0.30	0.76	1.00	0.57	0.97	1.46	SD 38%	S41
	Sweden	14	0.86	1.27	1.57	1.51	2.16	2.84	IS	H1
Cement	Denmark	6	0.24	0.54	0.81	0.11	0.32	0.57	AS	U1
	Finland	9	0.54	1.19	2.27	0.23	0.59	1.49	IS	M21
	Norway	4		0.81			0.51		IS	S23
	Sweden	16	0.54	1.11	4.54	0.65	1.08	2.19	AS	L11, S42
Concrete ballast ^c	Denmark	107	0.11	0.51	2.57	0.11	0.35	1.51	AS	U1
	Finland	266	0.19	0.92	3.95	0.04	1.05	6.11	AS	M21
	Sweden	306	0.19	1.30	4.51	0.08	1.95	12.51	AS	H1
Sand based Aerated Concrete	Denmark	2		0.49			0.27		IS	U1
	Finland	2	1.22	1.32	1.43	0.84	0.96	1.08	IS	M21
	Sweden	24	0.19	0.95	3.51	0.11	1.14	4.19	AS	S42
Alum shale based Aerated Concrete	Denmark	2		18.11			1.43		SO	U1
	Sweden ^d	70	16.76	35.14	70.82	0.81	1.91	3.11	AS	S42
	Sweden ^e	12	8.65	12.60	15.14	0.65	0.81	1.00	AS	S42
Plasterboards: Natural gypsum	Denmark	7	0.16	0.27	0.35	0.11	0.11	0.16	AS	U1
	Sweden	8	0.03	0.11	0.24	0.03	0.03	0.32	AS	S42
	Phosphogypsum	1		0.73			1.76		IS	S42
Gypsum: Natural	Denmark	6	0.11	0.19	0.27	0.11	0.11	0.11	AS	U1
	Finland	1		0.19			0.04		IS	M21
	Norway	2		0.30			0.08		IS	S23
	Phosphogypsum	4	0.65	4.81	8.92	0.09	0.32	0.59	IS	M22
Light-Weight Aggregate	Denmark	3	0.97	1.08	1.16	1.00	1.22	1.38	IS	U1
	Norway	12		1.38			1.51		IS	S42
	Sweden	6	3.65	4.60	5.27	4.14	4.43	5.03	IS	S42
Slag Aggregate	Finland	3	2.38	2.76	3.05	0.86	1.87	2.54	IS	M21
	Sweden	2	2.27	3.19	4.08	3.08	4.00	4.92	IS	U1
Insulation Material, wool, stone or glass	Denmark	5		1.08			1.08		IS	U1
	Finland	2	0.24	0.51	0.78	0.12	0.24	0.35	IS	M21
	Sweden	3	0.30	0.35	0.41	0.41	0.41	0.41	IS	S42
Tile	Finland	5	1.70	2.11	2.46	0.86	1.24	1.73	IS	M21
	Denmark	10	2.97	4.05	5.68	2.00	2.43	4.32	AS	U1
Flyash	Finland	2	0.008	0.011	0.014	0.005	0.019	0.032	IS	M21
	Denmark	13	0.59	1.78	2.92	0.59	1.49	1.97	IS	U1

^aNo. = Number of Samples; ^bAS = Adequate Sampling, IS = Inadequate Sampling, SD = Standard deviation, SO = Swedish Origin; ^cGravel, shingle, macadam; ^dIn production 1929-1975; ^eIn production 1974-1979; ^fThese original sources are as they appeared in the cited current source. The current source's bibliography contain these references. Source: (UN77)

TABLE 4-16. ^{222}Rn EXHALATION RATES OF VARIOUS BUILDING MATERIALS

Material	(liters) ^a		Surface/ Volume (m^{-1})	^{222}Rn Exhalation Rate (E)	
	V_b	V_d		(atoms $\text{m}^{-2}\text{s}^{-1}$)	(atoms $\text{kg}^{-1}\text{s}^{-1}$)
Ordinary concrete, gravel and sand from the sea, Danish deposits	47.7	152.3	30	167	2.38
Ordinary concrete, gravel and sand from the pits, Danish deposits	47.7	152.3	30	134	1.98
Ordinary concrete, composition unknown	37.1 32.0	163 168	34 30	156 184	2.22 2.30
Lightweight concrete, Swedish origin, alum shale: old type new type	20.6 75.0	179.4 125	28 32	4,089 1,436	210 71.8
Expanded clay concrete, LECA	44.6	73.6	35	22	1.19
Lightweight concrete, Danish origin, clay based	67.0 32.5	133.0 85.5	33 52	32 21	1.42 1.42
Bricks: solid type cavity type	109.8 11.4	90.2 106.8	67 161	2.3 0.97	0.08 0.08
Chipboard	63.9	54.1	175	0.34	0.09
Fiberboard	63.9	54.1	175	0.53	0.11
Gypsum board	71.5	46.5	178	0.61	0.11

 V_d = Volume of dead space. V_b = Volume of material being tested.

Source: (Jo80)

The contribution to the indoor radon concentration from the following home surfaces is calculated in the following examples. As shown, contributions from various surfaces can typically increase indoor radon air concentrations by 0.02 to 0.63 pCi/l. Greater contributions are possible in special cases.

1) From internal walls if made of by-product gypsum. Assume 100 m² of wall area.

- From Table 4-10, the radon emanation rate of by-product gypsum from 76 mm internal walls is 0.01 pCi/m²-sec per pCi/g of 226Ra content.

- From Table 4-11, the average 226Ra activity of phosphogypsum is 40 pCi/g.

$$\text{Radon Contribution} = (0.01 \text{ pCi/m}^2\text{-s per pCi/g})(40 \text{ pCi/g})(100 \text{ m}^2) \\ (3600 \text{ sec/hr})(\text{hr}/230,000 \text{ liter}) = \underline{0.63 \text{ pCi/l}}$$

2) From ceiling if made of 13 mm thick by-product gypsum.

- From Table 4-10, the radon emanation rate of this building material is 0.001 pCi/m²-s per pCi/g of 226Ra content.

- As before, the 226Ra activity of phosphogypsum is 40 pCi/g.

$$\text{Radon Contribution} = (0.001 \text{ pCi/m}^2\text{-s per pCi/g})(40 \text{ pCi/g})(92 \text{ m}^2) \\ (3600 \text{ sec/hr})(\text{hr}/230,000 \text{ liter}) = \underline{0.06 \text{ pCi/l}}$$

3) From slab foundation if made of heavy concrete 8 cm thick.

- From Table 4-10, the radon emanation rate of heavy concrete is 0.01 pCi/m²-s per pCi/g of 226Ra content.

- From Tables 4-12 and 4-13, an average value of the 226Ra activity is about 1.5 pCi/g.

$$\text{Radon Contribution} = (0.01 \text{ pCi/m}^2\text{-s per pCi/g})(1.5 \text{ pCi/g})(92 \text{ m}^2) \\ (3600 \text{ sec/hr})(\text{hr}/230,000 \text{ liter}) = \underline{0.02 \text{ pCi/l}}$$

4.4.3 Potable Water Supplies

This section summarizes available information on the concentration of radon in potable water supplies. It is important to note that much of the data was generated in areas suspected of

having high radon levels in the water, so concentrations listed may not be representative of the world's potable water supplies as a whole. However, they do serve as a conservative starting data base.

Tables 4-17 through 4-20 summarize available information on radon concentrations in world-wide potable water supplies. In the United States, typical radon levels in potable water supplies generally fall below 2,000 pCi/l, but concentrations greater than 300,000 pCi/l have been noted.

The relationship between the concentration of radon in water and the resulting radon concentration in air, and the parameters which affect that relationship, are defined and examined in detail in Chapter 5. In cases where the concentration of radon in the potable water is high, the water has often been shown to be the primary source of radon and progeny in household air.

The following example demonstrates the possible significance of radon in potable water supplies to indoor radon air concentrations.

Basis: $V_{\text{house}} = 230,000$ liters
 $f = 0.55$
 $\lambda = 1$ airchange/hour
 water usage = 19 liters/hr

$$C_a = C_w \frac{(0.55)(19 \text{ liter/hr})}{(1 \text{ airchange/hr})(230,000 \text{ liter/air change})}$$

C_w (pCi/l)	C_a (pCi/l)
2,000	0.1
50,000	2.3
300,000	13.6

Thus, radon in potable water supplies can contribute a significant amount to indoor radon concentrations.

TABLE 4-17. ²²²Rn IN POTABLE WATER SUPPLIES

Current Source	Original Source	C _w (pCi/l)	Basis or Key Assumptions
UN77	Ka73, Sn73	Normal = 20 to 1,000	Private and communal wells
MRC81		Average ²²² Rn (Maine) = 53,000 Average ²²² Rn (New Hampshire) = 101,000 Tap water = 100 to 7,500	In well water In well water Lawrence Berkeley study
EPA77		74± 0 to 2,000 26± >2,000 5± >10,000	Groundwater radon concentrations for U.S. excluding northeastern U.S. (438 samples). Many samples taken in areas thought to have high radon levels so the distribution is not representative of the entire U.S. groundwater supply.
EPA77		44± 0 to 2,000 56± >2,000 24± >10,000 2± >100,000	Northeastern U.S. mainly Maine and New Hampshire samples.
Ge80a		26± >2,000 5± >10,000	(438 wells) Data not necessarily representative of groundwaters used as public water supplies.
Ka80		Water Supply Plants 670 Private Dug Wells 1,600 Private Drilled Wells 17,000 Average Weighted for number of users 1,500	Drinking water in Finland
He78	Du76	Normal Range 0 to 30,000 Ranges up to 300,000	Excluding Maine and New Hampshire including Maine and New Hampshire
He83		Range 20 to 180,000	Radon concentrations in Maine only. Granitic areas had highest concentrations
Lo83a		Ranges up to 1,000,000	Personal communication with J. Lowry.

NOTES: *Refers to percent of samples collected.

TABLE 4-18
²²²Rn CONCENTRATION IN WATER

Location	Number of Wells with Radon Concentration in Water (pCi/l)				²²² Rn Concentration in Water		Ref. ^a
	<1000	1000 to 10,000	10 ⁴ to 10 ⁵	10 ⁵ to 10 ⁶	Maximum (pCi/l)	Average (pCi/l)	
Austria Salzburg					189	41	S22
Finland Helsinki and Vantaa	4	12	65	29		32,436	C3
Other areas	11	34	30	7	1,216,350	7,568	C3
Italy	41	16	2			2,162	M3
Sweden	155	17			4,055	514	K14
United States							
Aroostock, Maine	13	19			5,406	1,297	H10
Cumberland, Maine	1	6	7	2	156,774	27,030	H10
Hancock, Maine	1	3	11	1	124,338	37,842	H10
Lincoln, Maine	3	6	10	1	43,248	15,137	H10
Penobscot, Maine		10	6		64,872	14,596	H10
Waldo, Maine		5	9		137,853	29,733	H10
York, Maine		6	9		59,466	18,110	H10
All 7 counties	18	55	52	4	156,774	17,840	H10
North Carolina	84	117	10		45,951	2,703	S1

^a These original sources are as they appeared in the cited current source.
The current source's bibliography contain these references.

TABLE 4-19
DISTRIBUTION OF ^{222}Rn CONCENTRATION
IN DRINKING WATER IN FINLAND

<u>Water Specification</u>	<u>Number of Persons Served (million)</u>	<u>Radon Concentration (pCi/l)</u>	
		<u>Mean</u>	<u>Maximum</u>
Waterworks	3.18	676	43,248
Dug wells	1.39	1,595	43,248
Drilled wells	0.15	17,029	1,189,320
Drilled wells in Helsinki area	0.02	32,436	
Weighted average		1,514	

Source: (UN77)

TABLE 4-20. COMPILATION OF DATA BY SELECTED GROUPS^a

State	Area/Zone	Type of Well	No. of Radon Samples	Activity of ²²² Rn + Daughter Products Through ²¹⁴ Po (pCi/l)			No. of Radium Samples	Activity of ²²⁶ Ra (pCi/l)		
				Min.	Avg.	Max.		Min.	Avg.	Max.
Maine	all	all	228	0	53,700	884,000	55	0	65	730
NH ^b	all	all	26	2,510	101,000	1,130,000	21	0	4.8	23
Maine	all	drilled	128	1,120	87,600	884,000	33	0	66	440
Maine	all	dug	76	0	7,870	31,700	19	0	73	730
Maine	all	springs	18	0	18,800	113,000	2	0	1.0	2.0
Maine	Zone A	drilled	25	2,780	157,000	884,000	4	0	38	87
Maine	Zone A	dug	13	3,570	11,400	29,200	4	0	19	77
Maine	Zone B	drilled	7	14,400	69,800	228,000	0			
Maine	Zone B	dug	6	3,350	15,500	27,200	0			
Maine	Zone B	springs	3	21,700	27,400	31,500	0			
Maine	Zone A+B	drilled	32	2,780	138,000	884,000	4	0	38	87
Maine	Zone A+B	dug	19	3,350	12,700	29,200	4	0	19	77
Maine	Zone A+B	springs	3	21,700	27,400	31,500	0			
Maine	Zone C	drilled	15	2,760	152,000	859,000	8	0	160	440
Maine	Zone D	drilled	10	5,080	68,300	191,000	4	0	91	340
Maine	Zone D	dug	2	4,840	6,670	8,480	2	0	0	0
Maine	Area 1	drilled	17	1,120	13,500	82,400	9	0	23	95
Maine	Area 1	dug	21	0	4,810	18,300	11	0	77	730
Maine	Area 1	springs	6	0	4,040	13,300	2	0	1.0	2.0
Maine	Area 2	drilled	24	7,140	88,400	562,000	6	0	29	160
Maine	Area 2	dug	20	402	7,700	23,900	3			
Maine	Area 2	springs	7	1,820	11,200	36,200	0			
Maine	Area 3	drilled	30	2,450	49,100	278,000	0			
Maine	Area 3	dug	14	1,120	6,520	31,700	1	0	0	0
Maine	Area 3	springs	2	41,700	76,900	113,000	1	2.0	2.0	2.0
Maine	Zone G-1	drilled	36	2,780	152,000	884,000	9	0	75	400
Maine	Zone G-1	dug	17	1,350	10,400	29,200	5	0	15	77
Maine	Zone G-2	drilled	13	2,760	83,800	230,000	1	130	130	130
Maine	Zone G-2	dug	9	1,120	11,800	27,200	0			
Maine	Zone G-3	drilled	22	2,450	43,500	278,000	0			
Maine	Zone G-3	dug	6	1,240	12,500	31,700	0			
Maine	Metamorphic	drilled	44	3,510	58,200	256,000	10	0	71	440
Maine	Granitic	drilled	84	1,120	93,300	884,000	14	0	63	400
NH	all	drilled	17	2,560	142,000	1,130,000	12	0	6.9	23
NH	all	dug	3	6,180	30,100	68,800	3	0	4.1	12
NH	all	springs	1	6,130	6,130	6,130	1	5.7	5.7	5.7
NH	Grafton	all	3	2,510	4,940	6,180	3	0	1.9	5.7
NH	Dover	all	4	3,550	6,780	9,350	4	0	0.1	0.4
NH	in F.P. ^c	drilled	8	10,700	284,000	1,130,000	7	0	8.4	23
NH	out F.P.	drilled	9	2,560	25,500	136,000	5	0	4.6	15

^aConcentration of ²²²Rn in water samples.^bNH = New Hampshire^cF.P. = Fitchburg Pluton

Source: (Sm61)

4.4.4 Home Heating Fuels

^{222}Rn is a radioactive gaseous daughter product of ^{226}Ra which is found in naturally occurring uranium minerals throughout the earth's crust. Radon permeates porous geological formations and is collected along with methane in production wells for natural gas. When this natural gas is used in unvented appliances, the combustion products and radon are released within the home (Jo73).

A summary of reported data on radon concentrations in natural gas at production wells is given in Table 4-21.

The concentration of radon remaining in the natural gas when it reaches the consumer depends on many factors, including the concentration at the well-head, dilution, gas processing, transmission time, and storage time. Table 4-22 summarizes the concentration of ^{222}Rn in natural gas distribution lines.

Various factors affect the radon daughter concentrations in the home resulting from the use of natural gas. Chief among these are the concentration of radon and radon daughters in the gas, the volume of gas used, and the volume and ventilation rate of the home. Assuming that the radon concentration in the gas is 20 pCi/l and that 0.8 m³ of gas is consumed per day in an unvented kitchen range in a 230 m³ house with an air change rate of 1 hr⁻¹ leads to an average radon concentration in the house of 0.0028 pCi/l (Jo73).

On a similar basis, the household radon contribution from the use of kitchen ranges and space heaters was estimated to be 0.0129 pCi/l (Jo73). The higher percentages of expected indoor radon concentrations which would result from increased use of unvented space heaters may be derived from the data in Table 4-23.

4.4.5 Presence in Ambient Air

Another source of radon and radon progeny in household air is infiltration of ambient air. Table 4-24 summarizes available

TABLE 4-21
²²²Rn CONCENTRATIONS IN
 NATURAL GAS AT PRODUCTION WELLS

Area	²²² Rn Level (pCi/l)		Reference ^a
	Average	Range	
Colorado			
New Mexico	25	0.2-160	1
Texas, Kansas, Oklahoma	<100	5-1450	2
Texas Panhandle	---	10-520	3
Colorado	25.4	11-45	5-7
Project Gasbuggy Area	15.8-19.4	---	7
Project Gasbuggy Area	29.4	12-59	8
California	---	1-100	10
Gulf Coast (Louisiana, Texas)	5	---	11
Kansas	100	---	11
Wyoming	10	---	11
Overall Average	37		

^a These original sources are as they appeared in the cited current source.
 The current source's bibliography contain these references.

Source: (Jo73, UN77, UN82)

TABLE 4-22
²²²Rn CONCENTRATIONS IN
 NATURAL GAS DISTRIBUTION LINES

<u>Area</u>	<u>²²²Rn Level (pCi/l)</u>		<u>Reference^a</u>
	<u>Average</u>	<u>Range</u>	
Chicago	14.4	2.3-31.3	19
New York City	1.5	0.5-3.8	1
Denver	50.5	1.2-119	19
West Coast	15	1-100	10,19
Colorado	25	6.5-43	b
Nevada	8	5.8-10.4	7
New Mexico	45	10-53	1
Houston	8	1.4-14.3	c
Overall Average	23		

^a These original sources are as they appeared in the cited current source. The current source's bibliography contain these references.

^b Bernhardt, D.E., Radon-222 Concentrations in Natural Gas, Memorandum to D.T. Oakley, April 2, 1973.

^c Gesell, T.P., Op. Cit.

Source: (Jo73, UN77)

TABLE 4-23
COMPARISON OF INDOOR-AIR ^{222}Rn
CONCENTRATIONS FROM NATURAL GAS
WITH THE ICRP NO. 2 GUIDE OF 0.33 pCi/l

Degree-days ^a / day	Indoor Air ^{222}Rn Increase in Concentration ^b (pCi/l)		Percent of ICRP Guide
	Space Heaters	Heaters + Ranges ^c	
0	0.0	0.003	0.85
10	0.013	0.016	4.8
20	0.026	0.029	8.7
30	0.039	0.042	12.6
40	0.052	0.055	16.5
50	0.065	0.068	20.4
60	0.078	0.081	24.3
70	0.091	0.094	28.2
80	0.104	0.107	32.1
90	0.117	0.120	36.0
100	0.130	0.133	39.9

^aHeaters use about 0.354 m of natural gas per degree-day.

^bFor radon in natural gas at 20 pCi/l natural gas.

^cGas use in ranges produces an indoor radon concentration of about 0.003 pCi/l.

SOURCE: (Jo73)

TABLE 4-24. ^{222}Rn CONCENTRATIONS IN AMBIENT AIR

<u>Current Source</u>	<u>Original Source</u>	<u>Concentration (pCi/l)</u>	<u>Basis or Key Assumptions</u>
UN77		Average surface air = 0.07	World-wide average
Ho79		New York City outdoor concentrations = 0.1 to 0.2	
Yo82		Normal Radon = 0.25 Over Mineralized Areas = 0.75	United States
Ge80		Geometric Mean = 0.18 Arithmetic Mean = 0.195	Statistics based on eight measurements in the New York - New Jersey area
Sp80		Average = 0.7 Range = 0.3 to 1.6	Grand Junction, CO
Ku79	Ge77 Sp74 Ca75	Houston, TX 0.3 Grand Junction, CO 0.1 Raleigh, NC 0.2	
Jo73	UN72 Pe67	Range = 0.03 to 3.50 Daily Average Concentration = 0.3	Daily cycle of radon ambient air concentration
Ku80		Range = 0.04 to 1.0	United States
Wi77		Range = 0.5 to 1.5	General range

literature information on ambient radon concentrations. Table 4-25 has some additional information on ambient radon concentrations for particular locales within the United States. Ambient radon concentrations vary diurnally with a maximum normally occurring during the early morning hours and a minimum around noon. The range is typically one order of magnitude or less (UN77). Concentrations also vary seasonally due to variable ground exhalation rates, vertical atmospheric mixing, and frequency of inversions; but these effects are apparently somewhat localized. In general, the ambient radon concentration seems to average about 0.3 pCi/l with extremes as low as 0.0001 pCi/l and a high of 3.5 pCi/l. So, air that infiltrates into the home can contribute anywhere from 0.0001 to 3.5 pCi/l to the indoor air radon concentration.

Table 4-26 summarizes the various source contributions to indoor radon contributions along with comparable values estimated by another investigator. The most significant contributions to indoor radon air concentrations are from potable water supplies; from the soil, rock and home subsurface; and, in some cases, from building materials.

TABLE 4-25

 ^{222}Rn CONCENTRATIONS IN OUTDOOR AIR

<u>Location</u>	<u>Mean Value (pCi/l)</u> ^{222}Rn	<u>Ref.</u> ^a
United States (continental)		
Chicago	0.043 0.041	B6 B6
Washington	0.078 0.119	B6 L8
San Diego	0.003	B6
San Francisco	0.016	B6
Seattle	0.003	B6
Memphis	0.027	B6
New York City	0.130 0.100	G10 T3
Chester, NJ	0.214	F5
Cincinnati	0.259	G12
New Mexico	0.241	W6
Puerto Rico	0.0001	B6
Alaska	0.005	B6

^a These original sources are as they appeared in the cited current source. The current source's bibliography contain these references.

SOURCE: (UN82)

TABLE 4-26

SUMMARY OF SOURCE CONTRIBUTIONS TO THE
INDOOR RADON AIR CONCENTRATION

<u>Source</u>	<u>Calculated in This Report (pCi/l)</u>	<u>Br83 (pCi/l)</u>
Soil, Rock, Home Subsurface	0.01 - 2.7	0.05 - 2.4
Building Materials	0.02 - 0.7	0.005 - 0.5
Potable Water	0.1 - 13.6	0.2 - 28
Home Heating Fuels	0.003 - 0.0016	-
Ambient Air	0.0001 - 1.6	-

^aBasis: $V_{\text{house}} = 230,000$ liters
 $\lambda = 1$ airchange/hour

5.0 WATERBORNE RADON AND EFFECTS ON INDOOR AIR QUALITY

This chapter presents an analysis of the different factors that affect the transfer of radon from potable water supplies to the indoor air, and once in the air, the factors that affect its concentration. Major items to be discussed include the water-to-air transfer mechanism, identification of individual household radon sources and associated water-to-air transfer efficiencies, factors that affect the indoor radon air concentration, development of a mathematical relationship between the potable water radon concentration and that in the household air, and a review of monitoring data as it relates to water-to-air transfer efficiencies and the mathematical model.

5.1 WATER-TO-AIR-TRANSFER MECHANISM

The transfer of a gas such as radon from a region of higher concentration (potable water) to that of a lower concentration (household air) is called mass transfer. The mechanism of mass transfer depends upon the dynamics of the system in which it occurs. Mass can be transferred by random molecular motion in quiescent fluids, or it can be transferred from a surface into a moving fluid, aided by the dynamic characteristics of the flow. These two distinct modes of transport are referred to as molecular mass transfer and convective transfer and control the rate at which radon can be outgassed from water usage in typical household activities. For example, the radon in bath water must first diffuse to the surface (molecular mass transfer) and then be transported from the water's surface into the indoor air by air movement (convective mass transfer). Thus, the distance the radon must travel to reach a water-air-interface coupled with the area of exposure significantly impact the water-to-air transfer efficiency.

A comparison of the number of atoms of ^{222}Rn and its short-lived progeny per 100 pCi of activity can further explain molecular diffusion. Table 5-1 contains some characteristics of ^{222}Rn and its short-lived progeny. The following values for air and water are presented for the purpose of comparison and for assessing the magnitude of atomic dilutions:

Number of molecules of air/liter of air (STP): $2.7 \text{ E}+22$

Number of molecules of water/liter of water vapor: $2.7 \text{ E}+22$

Number of molecules of water/liter of liquid water: $3.35 \text{ E}+25$

Based on these values and the information given in Table 5-1, the ratio of the number of nuclide atoms versus the number of medium atoms can be made as follows:

100 pCi ^{222}Rn /liter of air is equivalent to
1 atom ^{222}Rn / $1.5 \text{ E}+16$ molecules of air

100 pCi ^{222}Rn /liter of water is equivalent to
1 atom ^{222}Rn / $1.9 \text{ E}+19$ molecules of liquid water

100 pCi ^{218}Po /liter of air is equivalent to
1 atom ^{218}Po / $2.76 \text{ E}+19$ molecules of air

100 pCi ^{214}Pb /liter of air is equivalent to
1 atom ^{214}Pb / $3.15 \text{ E}+18$ molecules of air

100 pCi ^{214}Bi /liter of air is equivalent to
1 atom ^{214}Bi / $4.3 \text{ E}+18$ molecules of air

100 pCi ^{214}Po /liter of air is equivalent to
1 atom ^{214}Po / $3.1 \text{ E}+25$ molecules of air

The following conclusions can be made from a comparison of these ratios:

- 1) Each atom of ^{222}Rn contained in water is surrounded by an enormous number of water molecules so that its diffusion pathway to the water-air interface is hindered.
- 2) There is virtually no likelihood for two or more of the extremely small number of "daughter" atoms to get together and form a clump. However, each daughter atom does have an electrical charge and very quickly attaches itself to one of the abundant dust particles in ambient air.

TABLE 5-1
CHARACTERISTICS OF ^{222}Rn AND ITS "SHORT-LIVED" PROGENY

Nuclide	T min	# Atoms per 100 pCi	Decay Mode	Alpha Energy (MeV)	Ultimate Decay (MeV-alpha)	WL
^{222}Rn	5500	(1.75 E+6)	(alpha)	(5.49)	(3.33 E+7)	-
^{218}Po	3.05	9.77 E+2	alpha	6.0	1.34 E+4	0.10
^{214}Pb	26.8	8.58 E+3	beta	-	6.60 E+4	0.52
^{214}Bi	19.6	6.28 E+3	beta	-	4.83 E+4	0.38
^{214}Po	2.7 E-6	8.8 E-4	alpha	7.69	6.7 E-3	0
Total Sum of "Ultimate Alpha Energy"					1.28 E+5	1.00

NOTES: Values (in parentheses) are not considered in computation of Working Level.

The major household activities that transfer radon to the indoor air along with typical transfer efficiencies are presented in the next section.

5.2 HOUSEHOLD RADON SOURCES AND ASSOCIATED WATER-TO-AIR TRANSFER EFFICIENCIES

Any time potable water is used in a house, radon can be transferred to the indoor air provided the water radon concentration is high enough to provide the driving force. This driving force is referred to as a concentration gradient and governs mass transfer. The quantity and frequency of water used in individual household applications along with their associated water-to-air transfer efficiencies determine each application's source strength. Typical household activities where potable water is used include showers, baths, toilets, dishwashers, laundry, cooking, and sinks. Table 5-2 summarizes literature information available on the transfer of radon from the water to the air during typical household activities.

The data in Table 5-2 indicates that household activities that produce the highest water-to-air interface areas result in higher radon transfer efficiencies. In other words, the higher the water-air interface area, the greater the mass transfer across the boundary layer and thus, the higher the transfer efficiency. Household activities that breakup the water-air interface or increase its area (dishwashing, laundry, shower) would produce the higher transfer efficiencies. This fact is verified by the data in Table 5-1.

Another factor influencing the radon transfer efficiency from water-to-air is the water temperature. Table 5-1 indicates that for a particular application, increasing the water temperature results in greater radon transfer efficiency. This fact was verified experimentally by Gesell (Ge80). Determinations of the loss rate of radon from water were made in the laboratory under the following conditions: 1) constant temperature, 2) constant water-air

TABLE 5-2
MEASURED ^{222}Rn WATER-AIR TRANSFER EFFICIENCIES
FOR TYPICAL HOUSEHOLD ACTIVITIES

	Transfer Efficiency (% ^{222}Rn Released)				
	EPA 77	Pa79	Ge80	He81	He82
<u>Laundry Washing:</u>					
Hot wash cycle (18 min) with soap		98.4±1.3			
Hot wash cycle (13 min) without soap		97.9±2.7			
Cold wash cycle (18 min) with soap		93.3±5.2			
Cold wash cycle (18 min) without soap		93.5±3.4			
Warm wash cycle (18 min) with soap		98.3			
Cold wash cycle (11 min) with soap		91.4			
Cold wash cycle (4 min) with soap		84.7			
Cold wash gentle-cycle with soap		78.7			
Cold wash gentle-cycle without soap		76.6			
Cold rinse regular cycle		80.9±17.4			
Cold rinse gentle cycle		62.2			
No specific description given			90 ^a	90 ^a	90 ^a
<u>Dishwasher:</u>					
Wash cycle		97.7±3.7			
Rinse cycle		98.5±2.1			
No specific description given			98	98	98
<u>Bath Tub:</u>					
Hot water		59.7			
Warm water		36.2			
Cold water		37.8			
No specific description given			47	30 ^a	30 ^a
<u>Shower:</u>					
Warm water		71.2±4.7			
No specific description given	91		63	65	65
<u>Sink:</u>					
Warm water		28.3			
No specific description given				30 ^a	10-15 ^a
<u>Toilets:</u>					
Tank		4.9±11.3			
Bowl		23.6±6.5			
No specific description given			30	30 ^a	30 ^a
<u>Drinking and Kitchen:</u>					
No specific description given			30		
<u>Cleaning:</u>					
No specific description given			90		
Overall Weighted Average for All Household Uses		62.5	52	59	59

NOTES: ^aEstimated

interface area, and 3) minimum water agitation. Figure 5-1 summarizes the data for temperatures of 80°, 50° and 22°C. The data are consistent with a temperature-dependent exponential loss rate. It is interesting to note the slow loss of radon under unagitated conditions at 22°C (room temperature).

Another experiment was performed at room temperature only under agitated conditions. After 15 minutes of agitation, only 40 percent of the initial radon content was lost. Thus, household activities that use agitated room temperature water will only release about 40 percent of the initial radon after 15 minutes. This is verified by the data summarized in Table 5-1 as household activities using warm or cold water (bathtub, sink, toilet) have radon transfer efficiencies of 50 percent or less. Figure 5-2 illustrates this relationship between radon loss and water temperature.

5.3 FACTORS THAT AFFECT THE INDOOR RADON AIR CONCENTRATION

This section of the report presents the factors that affect the indoor radon air concentration assuming transfer of radon from potable water supplies is the only source of interest. The derivation of the steady-state relationship between radon concentrations in household air and the radon emanating from potable water supplies is documented in the literature (Ge80, He82). This derivation leads to the following equation:

$$C_a = \frac{(C_w)(f)(V_w)}{(\lambda)(V_{\text{house}})} \quad [1]$$

where

C_a = Concentration of radon in air (pCi/l)

C_w = Concentration of radon in water (pCi/l)

f = Transfer efficiency of radon from water to air

V_w = Household water usage (liters/hr)

λ = Ventilation rate air changes per hour (hr⁻¹)

V_{house} = Volume of house = volume of air change (liters)

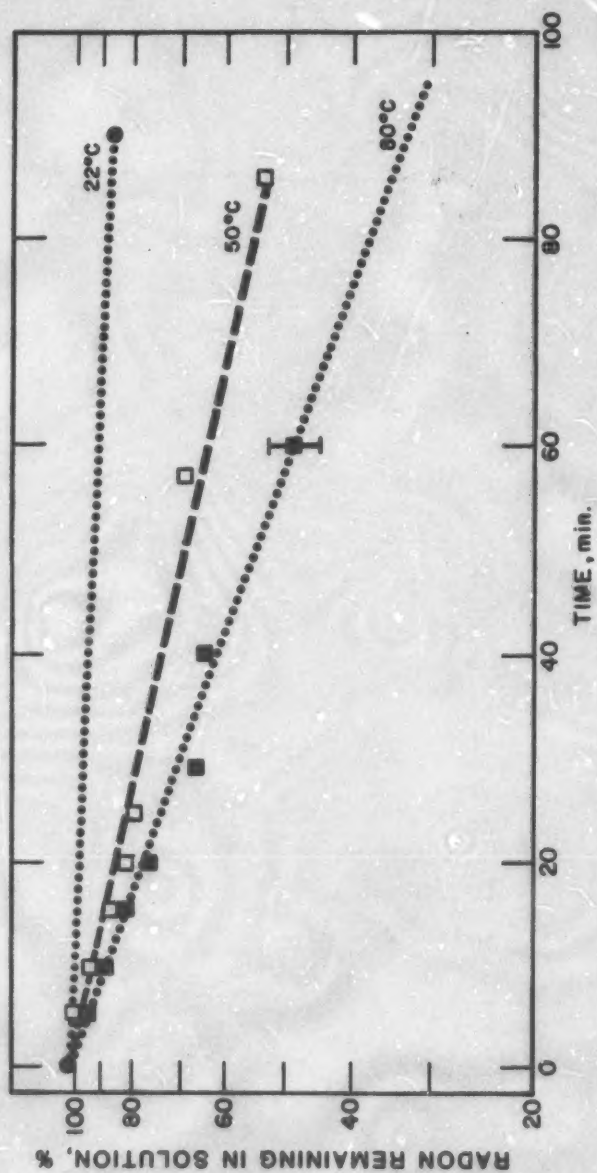


Figure 5-1

Loss of Radon with time from a 750 ml
unagitated water sample held at
three constant temperatures

SOURCE (Ge80)

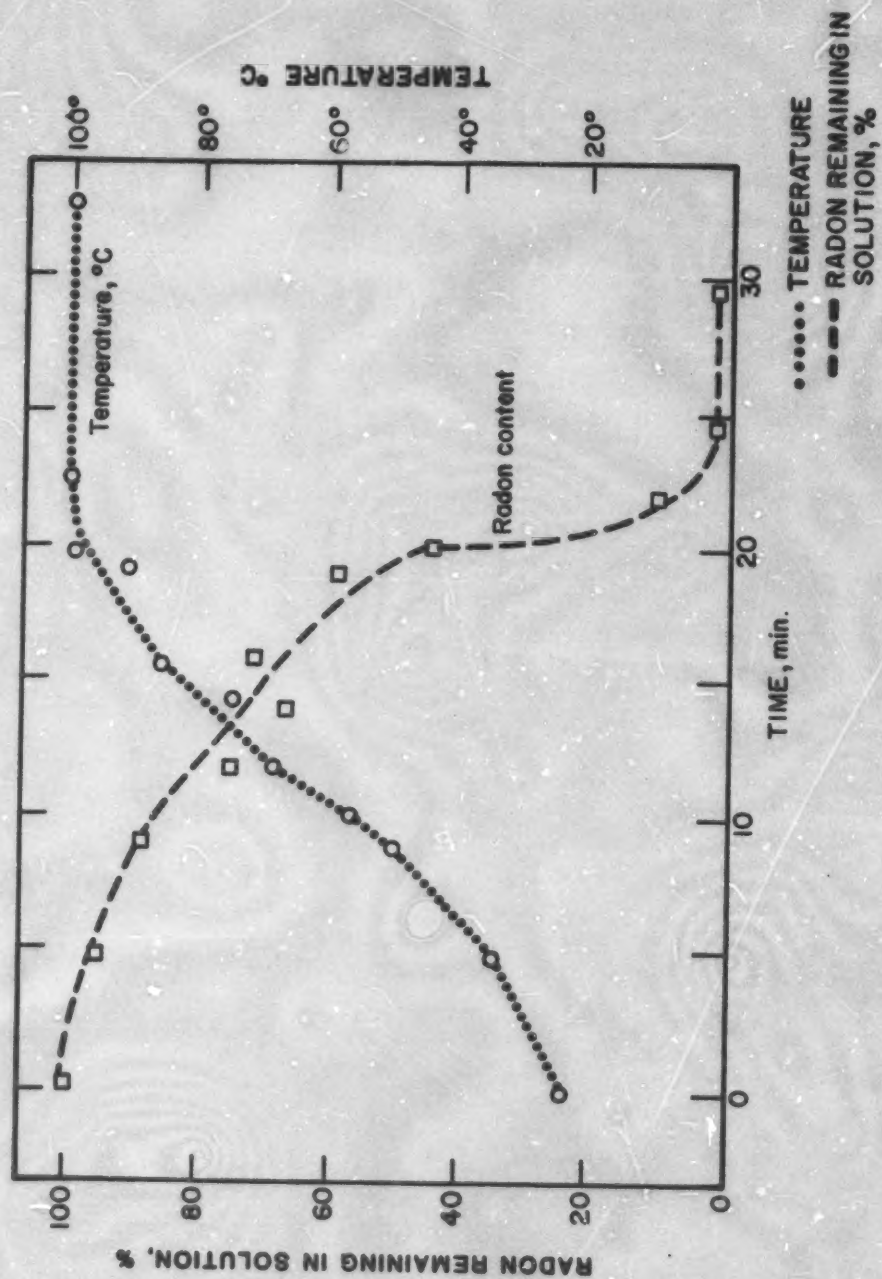


Figure 5-2

Loss of Radon as water is heated and boiled

SOURCE (G-80)

From Equation 1, which assumes that potable water is the only source of indoor radon and steady-state conditions, it is evident that the concentration of radon in household air depends on the concentration of radon in the potable water, the average transfer efficiency of radon from water to air, the household water usage, the ventilation rate and the volume of the house. Factors that affect the transfer efficiency of radon from water to air were previously discussed in Section 5.2, and overall weighted averages including all household uses, derived by several investigators, are presented in Table 5-2. A typical average value for the transfer efficiency is 0.55 (Ge80, He81, He82, Br83).

The daily volume of water that a person uses will vary depending on the individual's needs. For example, a housewife with several small children may use large quantities of water for the laundry of diapers, whereas a bachelor in an apartment may send his clothes out for laundering.

The concentration of radon in the potable water supply depends upon the source and location of the potable water. For example, many private wells have higher radon concentrations than municipal water supplies, river and lakes. Numerous studies have been conducted in Maine that show groundwater drawn from wells in granitic areas have high radon concentrations. So, the high background uranium content (%, radium) in the geographic areas from which the potable water is supplied, are linked with high radon concentration in the water.

The ventilation rate is an indication of the tightness of the home. The tightness of a home depends on how well ventilation or infiltration can be minimized and not on the amount of insulation used. Thus, the ventilation rate can be decreased or increased by varying the amount of air infiltration through cracks, around windows, doors and joints in construction. The infiltration of outside air can be decreased by blocking and minimizing these air

passageways using weather stripping, caulking or some similar technique (Ha81). The tightness of a house often varies with house design, geographical location and season.

The volume of a house depends on the individual needs and affordability of the resident. The household water usage, ventilation rate and house volume will vary from place to place, but for the purposes of evaluation, the following values will be assumed typical:

$$V_w = 9.5 \text{ liters/hr/person (or 60 gal/day/person)}$$

$$\lambda = 1 \text{ air change/hour}$$

$$V_{\text{house}} = 75,000 \text{ liters/person}$$

5.4 REVIEW OF PREVIOUS STUDIES RELATING TO POTABLE WATER RADON CONCENTRATION AND THAT IN THE HOUSEHOLD AIR

This section of the report summarizes literature data examined relating the potable water radon concentration (C_w) and radon concentration in the household air (C_a). Table 5-3 summarizes this data along with major experimental conditions or assumptions. A brief description of each of the studies listed in Table 5-3 is presented in chronological order in the following section.

UN77 - Assuming that the radon concentration in the water is 1000 pCi/l and is completely released into the air, a water consumption in the house of 1000 liters/day, a house volume of 230,000 liters, and an air change rate of 1 hr⁻¹, the average concentration of radon due to water supplies in the air of such a house can be roughly estimated at 0.2 pCi/l. The factor C_a/C_w therefore would have a value of 2.0×10^{-4} .

The C_a/C_w derived in UN77 is purely theoretical and is likely to be an overestimation since it assumes a transfer efficiency from water to air of 100 percent ($f=1.0$), whereas most investigators agree that a weighted average value of approximately 55 percent ($f=0.55$) is appropriate.

TABLE 5-3
SUMMARY OF C_a/C_w LITERATURE DATA

Source	C_a (pCi/l)	C_w (pCi/l)	C_a/C_w	Experimental Conditions/Basis																					
UN77	0.2	1,000	1.0×10^{-4}	Series of assumptions: 4 people, water use = 1000 liters/day, 230,000 liters = V_{house} , $\lambda = 1 \text{ hr}^{-1}$, $f = 1.0$.																					
He78	0.09 0.3 0.7 4.5 5.0 10.0	100 3,000 9,000 60,000 85,000 85,000	9.0×10^{-4} 1.0×10^{-4} 0.78×10^{-4} 0.75×10^{-4} 0.59×10^{-4} 1.2×10^{-4}	$\lambda = \text{unknown}$, actual data based on measurements of C_a in the same room as the source. Lead authors to conclude $C_a/C_w = 10^{-4}$.																					
He79	2.4 ± 1.2 2.6 ± 0.7 10.3 ± 1.6 3.9 3.3	60,000 1,480 24,810 87,430 32,670	$(0.4 \pm 0.2) \times 10^{-4}$ $(18 \pm 5) \times 10^{-4}$ $(4 \pm 2) \times 10^{-4}$ 0.45×10^{-4} 1.0×10^{-4}	$\lambda = 3.0 \text{ hr}^{-1}$ $\lambda = 1.1 \text{ hr}^{-1}$ $\lambda = 1.0 \text{ hr}^{-1}$ $\lambda = 2.1 \text{ hr}^{-1}$ school $\lambda = \text{unknown}$ } 24 hr radon values in these dwellings. Wrenn-Spitz-Lundum measurements.																					
Pa79	0.18 0.42 0.78 1.3 0.92 0.40 0.18	10,000 10,000 10,000 10,000 10,000 10,000 10,000	0.18×10^{-4} 0.42×10^{-4} 0.78×10^{-4} 1.3×10^{-4} 0.92×10^{-4} 0.40×10^{-4} 0.18×10^{-4}	$\lambda = 2.0 \text{ hr}^{-1}$ $\lambda = 1.0 \text{ hr}^{-1}$ $\lambda = 0.5 \text{ hr}^{-1}$ $\lambda = 0.25 \text{ hr}^{-1}$ $V_{house} = 1.4 \times 10^5$ $V_{house} = 3.4 \times 10^5$ $V_{house} = 6.6 \times 10^5$ } $V_w = 23.3 \text{ liters/hr}$ $f = 0.625$ $V_{house} = 4 \times 10^5 \text{ liter}$ $V_w = 23.3 \text{ liters/hr}$ $f = 0.625$ $\lambda = 1.0 \text{ hr}^{-1}$																					
Ge80	1 0.51 0.11 0.05 0.01 0.35 0.04 0.18 0.10	10,000 1,000 1,000 1,000 1,000 1,750 700 2,000 2,000	1.0×10^{-4} 5.1×10^{-4} 1.1×10^{-4} 0.5×10^{-4} 0.1×10^{-4} 2.0×10^{-4} 0.57×10^{-4} 0.90×10^{-4} 0.5×10^{-4}	Estimation Basis, $V_{house} = 200,000 \text{ liters}$ <table><tr><th></th><th>$V_{house} \text{ (liters)}$</th><th>$\lambda \text{ (hr}^{-1})$</th></tr><tr><td rowspan="4">Calculated</td><td>150,000</td><td>0.25</td></tr><tr><td>340,000</td><td>0.50</td></tr><tr><td>340,000</td><td>1.0</td></tr><tr><td>680,000</td><td>2.0</td></tr><tr><td rowspan="4">Actual Measurements</td><td>175,000</td><td>0.25</td></tr><tr><td>340,000</td><td>1.0</td></tr><tr><td>340,000</td><td>0.5</td></tr><tr><td>500,000</td><td>1.0</td></tr></table>		$V_{house} \text{ (liters)}$	$\lambda \text{ (hr}^{-1})$	Calculated	150,000	0.25	340,000	0.50	340,000	1.0	680,000	2.0	Actual Measurements	175,000	0.25	340,000	1.0	340,000	0.5	500,000	1.0
	$V_{house} \text{ (liters)}$	$\lambda \text{ (hr}^{-1})$																							
Calculated	150,000	0.25																							
	340,000	0.50																							
	340,000	1.0																							
	680,000	2.0																							
Actual Measurements	175,000	0.25																							
	340,000	1.0																							
	340,000	0.5																							
	500,000	1.0																							
Ka80 (Finland)	unknown unknown unknown		1.4×10^{-4} 0.6×10^{-4} 0.07×10^{-4}	Housewives and small children. Other persons Population-weighted coefficients for all of Finland.																					
Mc80	0.5 3.2 0.6 2.0 4.1 2.5 0.5 3.4 2.2 0.7 1.2 0.6 19.1 6.6 1.5 3.0 3.3 1.2	150,000 164,000 152,000 158,000 160,000 148,000 129,000 43,000 98,000 370,000 190,000 314,000	0.032×10^{-4} 0.2×10^{-4} 0.039×10^{-4} 0.13×10^{-4} 0.24×10^{-4} 0.17×10^{-4} 0.034×10^{-4} 0.26×10^{-4} 0.51×10^{-4} 0.16×10^{-4} 0.12×10^{-4} 0.061×10^{-4} 0.52×10^{-4} 0.18×10^{-4} 0.079×10^{-4} 0.16×10^{-4} 0.11×10^{-4} 0.038×10^{-4}	Nova Scotia, Canada trailers, actual measurements School Conventional homes School Conventional homes																					

TABLE 5-3
SUMMARY OF C_a/C_w LITERATURE DATA
(Continued)

Source	C_a (pCi/l)	C_w (pCi/l)	C_a/C_w	Experimental Conditions/Basis
NRC81	0.2	1,000	1.0×10^{-4}	General statement
He81			$0.75 \pm 0.1 \times 10^{-4}$	Average of 18 homes in Maine.
	1.9	52,000	0.37×10^{-4}	Normalized to $\lambda = 1 \text{ hr}^{-1}$ Graphically: $(0.6 \pm 0.1) \times 10^{-4} = C_a/C_w$ Add 25% for weak sources $(0.75 \pm 0.1) \times 10^{-4} = C_a/C_w$
	1.7	17,000	1.0×10^{-4}	
	3.2	27,000	1.2×10^{-4}	
	0.7	6,500	1.2×10^{-4}	
	4.5	28,000	1.6×10^{-4}	
	3.0	18,000	1.7×10^{-4}	
	<0.3	330	9.1×10^{-4}	
	<0.3	330	9.1×10^{-4}	
	<0.3	330	9.1×10^{-4}	
	1.5	22,000	0.68×10^{-4}	
	1.5	25,000	0.60×10^{-4}	
	1.0	8,000	0.13×10^{-4}	
	5.0	28,000	0.18×10^{-4}	
	<0.3	330	9.1×10^{-4}	
	3.8	52,000	0.73×10^{-4}	
	0.85	17,000	0.50×10^{-4}	
	1.6	27,000	0.59×10^{-4}	
	0.35	6,500	0.54×10^{-4}	
	2.0	28,000	0.71×10^{-4}	
	1.0	18,000	0.56×10^{-4}	
He82			$(0.8 \pm 0.2) \times 10^{-4}$	Normalized to $\lambda = 1 \text{ hr}^{-1}$, corrected radon bursts by 33% to account for radon from all water.
UN82	-	-	1.5×10^{-4}	$f = 1.00$ (NEA78)
	-	-	1.0×10^{-4}	(Du76)
	229	138,000	20.6×10^{-4}	avg. C_a/C_w for 32 rooms, situations where much water used (showers).
	(avg. 32 obs.) (avg. 20 homes)			
	78	138,000	5.64×10^{-4}	avg. C_a/C_w for 47 rooms, situations where little water used (cooking).
	(avg. 47 obs.)			
	5.92	138,000	0.60×10^{-4}	avg. C_a/C_w for 20 living rooms, situations where no water used (An78).
	(avg. 20 obs.)			
He83			1.3×10^{-4}	avg. C_a/C_w in 70 homes discounting other sources (not normalized for λ .)

He78 - Hess, et al., present an early paper reporting results of their studies of the relationships between radon-laden groundwater in the State of Maine and resulting airborne concentrations in homes. The results of a sampling and analysis program to determine ^{222}Rn content in well samples are described. One hundred twenty-eight samples were collected from wells in several Maine counties. Each of the samples was collected in duplicate using standardized procedures. Analysis was by liquid scintillation counter according to the methods of Prichard and Gesell.

Of the 128 pairs of samples collected, 28 (22%) varied by more than 10 percent. The authors indicate variation in analysis of duplicate samples can be caused by loss of ^{222}Rn from the sample collection vial (improper capping), failure to remove sufficient old water from the storage tank before collecting the sample, and improper counting. The variation is cited here to point out some of the potential sources of error in determination of the air-to-water concentration ratio C_a/C_w .

As reported in He78, experiments were conducted to evaluate the relationships between radon concentration in water and resulting concentration in air. Results are reported for six different concentrations of ^{222}Rn in water ranging from 100 to 85,000 pCi/l. The results are presented in Table 5-3. Concentrations in air exclude background concentrations. Other authors suggest that there is a definite relationship between water and air ^{222}Rn concentrations for ^{222}Rn concentrations in water (C_w) exceeding 1000 pCi/l but that this relationship deteriorates for lower radon water concentrations. Hess' findings verified this statement. Based on his results, the air-water concentration ratio (C_a/C_w) ranged from 0.59×10^{-4} to 1.2×10^{-4} when $C_w > 1000$ pCi/l, while C_a/C_w was equal to 9×10^{-4} for $C_w = 100$ pCi/l.

The authors concluded the ^{222}Rn in air "was found to have a concentration equivalent to 10^{-4} of that in the water." This conclusion is based on measurements in the room where the shower is

located. The ventilation rate for the room was not reported. As the radon is diffused throughout the household, the incremental increase in C_a would be more difficult to measure and subject to variability for numerous reasons.

He79 - The authors report results of experiments to correlate C_w with C_a in ten homes. Results for the five homes where C_w exceeded 1000 pCi/l are shown in Table 5-3. As shown, the ratio of air to water concentrations measured varied from 0.4×10^{-4} to 18×10^{-4} . The variability is thought to be primarily due to the unknown magnitude of contribution from soil. The volumes of the homes and water use rates were not reported, so that a comparison of theoretical versus measured values for C_a/C_w is not possible.

Pa79 - Partridge, Horton and Sensintaffer conducted field experiments with the primary objective of determining the fraction of radon released from water (f) during typical household activities, including clothes washing, dish washing, tub, sink, shower, and toilet. As presented in Section 5.2, a weighted average value for all sources of f (62.5%) was derived. The authors then applied their findings concerning the term f , together with other assumptions identified in Table 5-2, to predict C_a/C_w for various ventilation rates ($\lambda = 0.25 - 2.0 \text{ hr}^{-1}$) and dwelling volumes ($V_{\text{house}} = 1.4 \times 10^5 - 6.6 \times 10^5 \text{ liters}$). The predicted factor C_a/C_w varies from 0.18×10^{-4} to 1.3×10^{-4} . Their calculations demonstrate the importance of λ and V_{house} on C_a/C_w .

Ge80 - The authors present the results of theoretical computations of C_a/C_w for four different types of dwellings, including a small apartment ($C_a/C_w = 5.1 \times 10^{-4}$), new brick home ($C_a/C_w = 1.1 \times 10^{-4}$), old frame house ($C_a/C_w = 0.5 \times 10^{-4}$), and large older structure ($C_a/C_w = 0.1 \times 10^{-4}$). The computations incorporate different representative ventilation rates (λ) and dwelling volumes for each type of structure, but assumed the same water to air transfer efficiency ($f = 0.52$) and water use (37.1 liters/hr) for each dwelling. The authors conclude that C_a/C_w can vary by a factor of 50, depending on dwelling type.

Next, experiments in the laboratory and in homes were conducted to verify model predictions. The following observations were noteworthy:

- 1) Air measurements (C_a) were conducted by Wrenn precipitator, which has a lag time and can introduce some error when ventilation rates are high or humidity is less than 30 percent.
- 2) Experiments in the laboratory and home varied by up to 120 percent compared with theoretical computations for the same locations.
- 3) Long-term measurements in homes indicate diurnal patterns related to water use cause fluctuations in C_a by a factor 5.

Ka80 - This paper reports results of derivation of C_a/C_w by investigators in Finland. Two concentration ratios were reported. The first, 1.4×10^{-4} , applies to housewives and small children; the second, 0.6×10^{-4} , applies to other persons. The ratios "take into account the time spent indoors, especially in places where water is used extensively." A weighted average, 0.87×10^{-4} , is also reported, and due to uncertainty, the authors adopted 1.0×10^{-4} for use in subsequent health risk calculations.

The utility of the numbers reported above is limited by several factors. Since the studies were in Finland, there may be inherent differences in water use rates, types of uses, home ventilation rates, water temperatures, home sizes, etc., as compared with the United States.

Mc80 - This paper reports results of actual measurements of C_a and C_w in six conventional residences, five trailers, and two schools in Nova Scotia, Canada in January 1979. Radon concentrations in tap water (C_w) were high, ranging from 43,000 to 370,000 pCi/l. It was believed that water was the major source of radon in the air of the homes.

Results are noteworthy because the concentration ratios (C_a/C_w) measured are lower than those predicted or measured by most other investigators. C_a/C_w ranged from $(0.032 \text{ to } 0.24) \times 10^{-4}$ for trailers and $(0.038 \text{ to } 0.52) \times 10^{-4}$ for homes. Information concerning ventilation rates and water use patterns was not presented. The low C_a/C_w ratios are not explained in the paper but may be due to very high ventilation rates ($\lambda > 2$), a low ratio of water use to home size, low water transfer efficiency (preference of the residents to baths rather than showers, absence of dishwashers or laundry equipment), possible uncertainty due to measurement techniques, or other factors.

NRC81 - Although this reference states "a concentration of 10,000 pCi/l can raise average indoor ^{222}Rn content by about 1 nCi/m³" ($C_a/C_w = 1.0 \times 10^{-4}$), it provides no source or derivation of this value.

He81 - This report presents the results of the Hess, et al., 1978-1980 project to estimate radon exposure levels in 18 homes. Samples were collected in living rooms, or occasionally kitchens, of homes in the State of Maine, mostly during the winter (when home ventilation rates are low). The homes were known to have water supplies with significant ^{222}Rn concentrations ($C_w = 6,000 \text{ to } 52,000 \text{ pCi/l}$ for most of the homes), but many were built on granite bedrock, and the home subsurface was also thought to be a significant contributor to C_a in some of the homes.

The concentration of ^{222}Rn in air was monitored continuously by Wrenn detector for up to 7 days in each of the 18 homes. Grab samples of the air were also collected, by 2 cell. Samples of well water were single grabs, and loss of radon associated with various water uses was measured by liquid scintillation measurement of the water before and after use. Residents recorded the times of major water use in order to correlate water use with air exposures.

The authors observed that in homes where water was believed to be the primary source of ^{222}Rn , a spike in air concentration occurs shortly after use of a shower, dishwasher, or clothes washer. This spike typically has a magnitude of 5 to 10 times background. The duration of the spike depends on the ventilation rate. In homes with low ventilation rates and significant ^{222}Rn sources other than water, air concentrations are continuously high and water use will cause negligible elevation in C_a . These observations are more apparent with use of the Z cell, which has a quick response time, as opposed to the Wrenn detector which has a much slower response.

He81 is significant in that it attempts to isolate the contribution of water use to indoor ^{222}Rn concentration and normalize the air to water concentration ratio C_a/C_w to a standard ventilation rate ($\lambda = 1 \text{ hr}^{-1}$). This was done by the measurement of ^{222}Rn in water before and after various uses (shower, dishwasher, laundry), measurements of indoor air concentrations, and theoretical computations. The results are summarized as follows.

- 1) The ratio of C_a to C_w in 16 cases where $C_w > 6000 \text{ pCi/l}$ had a mean value of 4.61×10^{-4} and a median value of 2×10^{-4} . (These values are a result of all ^{222}Rn sources, not just ^{222}Rn in water.)
- 2) C_a/C_w , attributable only to significant water uses (shower, laundry, dishwasher), had a mean value of 1.12×10^{-4} and a median value of $(1.0 - 1.08) \times 10^{-4}$.
- 3) C_a/C_w , attributable only to significant water uses and normalized to $\lambda = 1 \text{ hr}^{-1}$, had a value of $(0.6 \pm 0.1) \times 10^{-4}$. This value neglects contributions from kitchen and bathroom sinks, toilets, or other relatively minor sources which were difficult to quantify.
- 4) The authors assume that ^{222}Rn emissions from minor sources add approximately 25 percent to overall ^{222}Rn air concentrations. Therefore, they conclude a reasonable value for C_a/C_w from all

water sources, normalized to $\lambda = 1 \text{ hr}^{-1}$, is $(0.75 \pm 0.1) \times 10^{-4}$. This value is an average and excludes variations due to number of residents in the home, size of home, and differing habits of water use.

He81 provides extensive information concerning the derivation of C_a/C_w , but also demonstrates some of the potential sources of uncertainty in deriving C_a/C_w . These include:

- 1) While C_a is measured frequently and through several techniques, the value for C_w appears to be based on a single grab sample.
- 2) The differences in the magnitude and lag time of response for alternative methods of measuring C_a may affect the value of C_a/C_w , particularly when λ is large.
- 3) It has been shown that measurement of C_a is dependent on humidity and requires application of a correction factor.
- 4) Methods of measuring and normalizing for λ have an unknown degree of uncertainty.

He82 - In this paper, Hess, et al., report results of studies to correlate C_w and C_a measured in approximately 70 to 85 homes in the State of Maine. A significant feature of this study is that individual measurements of C_a were made by track etch cups in five different areas of each home, including the basement (arithmetic mean = 6.4 pCi/l), bathroom (3.4 pCi/l), bedroom (3.0 pCi/l), kitchen or living room (3.1 pCi/l), and outside (0.8 pCi/l). The following observations were found by the authors to be statistically valid:

- 1) The basement C_a in the study was nearly twice as high as the average C_a in the other rooms. This is thought to be due to non-water sources and/or low ventilation rates.

2) Radon in water supplies was found to be a source of some, but probably not all, radon in air. For example, bathroom C_a 's suggest a background radon level of at least 1.6 pCi/l due to non-water sources.

3) C_a is significantly correlated with C_w for the houses in the study, with a regression line suggesting $C_a/C_w = 1.07 \times 10^{-4}$ for these homes.

In He82, the authors also slightly revise their conclusions concerning C_a/C_w (derived in He81) based on the results of continuous monitoring conducted at 18 homes. Measurements had indicated that sources which liberate radon in large observable bursts (showers, laundries, dishwashers) result in a C_a/C_w of $(0.6 \pm 0.1) \times 10^{-4}$; and that slowly and weakly emanating sources (sinks, toilets, baths) account for an additional 25 percent, resulting in an overall $C_a/C_w = (0.75 \pm 0.1) \times 10^{-4}$. In He82, the authors cite the work presented in Kr78 to revise the contribution of these weak sources upwards to 33 percent of strong sources, resulting in an overall $C_a/C_w = (0.8 \pm 0.2) \times 10^{-4}$, normalized to $\lambda = 1 \text{ hr}^{-1}$.

UN82 - Some other estimates of C_a/C_w , not previously cited in this report, are briefly presented in UN82. For example, NEA78 calculates $C_a/C_w = 1.5 \times 10^{-4}$ if $f=1.0$ (unrealistic). Du76 calculates $C_a/C_w = 1.0 \times 10^{-4}$, but no details are available. Data presented in An78 relates C_w in 20 homes in Finland with C_a in bathrooms, kitchens, and living rooms. The results indicate average values for C_a/C_w range from 20.6×10^{-4} in bathrooms, to 5.64×10^{-4} in kitchens, to 0.60×10^{-4} for living rooms. It appears that these values exclude contributions from ^{222}Rn sources other than water. The effects of water use patterns and ventilation rates are not reported.

Pr83 - Additional interpretations are provided of the study of C_a and C_w in 70 to 85 homes in Maine reported previously in He82. Average room concentrations reported in He82 are revised downward

in Pr83 through deletion of a few observations which were thought to be extraordinarily high. Average concentrations reported include: bedroom, 1.94 pCi/l; bathroom, 2.41 pCi/l; living room/kitchen, 2.10 pCi/l; basement, 3.74 pCi/l, and outside, 0.63 pCi/l. The average C_w in these homes was 16,380 pCi/l.

Although the factor C_a/C_w is not derived for each of the homes studied, the following conclusions are noteworthy.

- 1) Bathroom concentrations are higher than bedroom and kitchen/living room measurements at the 99 percent confidence level.
- 2) Bedroom and kitchen/living room concentrations did not differ from each other with statistical significance.
- 3) All indoor concentrations are higher than outdoor concentrations at the 99 percent confidence level.

He83 - This report contains much of the same information published in other papers by this author and his colleagues. Two new conclusions concerning the study of 70 to 85 homes, previously reported in He82, are presented. These include:

- 1) For the homes studied, the water and air concentrations are correlated and can be fit by a linear regression line with slope of 1.3 pCi/l air per 10,000 pCi/l water, with y-intercept at 1.43 pCi/l air (C_a/C_w not normalized for λ).
- 2) Occasional radon daughter measurements in the homes studied indicate equilibrium fractions ranged from 0.33 to 0.18 in these homes.

5.5 DEVELOPMENT OF A MATHEMATICAL RELATIONSHIP BETWEEN THE POTABLE WATER RADON CONCENTRATION AND THAT IN THE HOUSEHOLD AIR

As presented in Section 5.3, there are many variables that influence the ratio between the radon concentration in the indoor air and the concentration found in the water (C_a/C_w). Section 5.4

summarized the available data on which many investigators have based their empirical "10-4" as the value of C_a/C_w . The remainder of this section will present the mathematical equation relating C_a to C_w . The relationship between the air-to-water concentration ratio and the other major variables will then be graphically presented to illustrate the dependence of this ratio on these variables.

As presented in Section 5.3, Equation 1 read:

$$C_a = \frac{(C_w)(f)(V_w)}{(\lambda)(V_{\text{house}})} \quad [1]$$

which can be rewritten as,

$$\frac{C_a}{C_w} = \frac{(f)(V_w)}{(\lambda)(V_{\text{house}})} \quad [2]$$

where

- f = transfer efficiency of the radon from the water to the air
- V_w = household water usage (liters/hr)
- λ = air changes/hr (hr-1)
- V_{house} = volume of air change or volume of house (liters)

Table 5-4 presents typical and maximum and minimum reasonable values of each of these variables. These values are then inserted into Equation 2 to generate the minimum, typical and maximum values of the ratio C_a/C_w , as shown in Table 5-5. This table indicates that under typical conditions, the ratio C_a/C_w closely approximates the "10-4" empirical value and for our assumptions is 0.7×10^{-4} . For the remainder of this report, conditions that generate a minimum value for the ratio C_a/C_w will be called "conservative" and those that generate a maximum value will be called "liberal" conditions.

Figure 5-3 shows the variability of the ratio C_a/C_w for varying water transfer efficiency (f) when the other variables are kept constant as illustrated in Table 5-5. Figure 5-4 shows the variability of the ratio C_a/C_w for varying air change rates (λ)

TABLE 5-4
VARIABLE RANGES

Parameter	Minimum Values	Typical Values	Maximum Values
f	0.25	0.55	1.0
V _w (liter/hr/person)	4.75	9.5	19
V _{house} (liters/person)	37,500	75,000	150,000
λ (air change/hr)	0.2	1.0	2.0

TABLE 5-5
C_a/C_w RANGE

Parameter	Conservative Variables that Generate Minimum C _a /C _w	Typical Variables	Liberal Variables that Generate Maximum C _a /C _w
f	0.25	0.55	1.0
V _w (liters/hr/person)	4.75	9.5	19
V _{house} (liters/person)	150,000	75,000	37,500
V _w /V _{house} (hr ⁻¹)	3.17 x 10 ⁻⁵	1.27 x 10 ⁻⁴	5.07 x 10 ⁻⁴
λ air change/hr	2.0	1.0	0.2
C _a /C _w	3.96 x 10 ⁻⁶ or .0396 x 10 ⁻⁴	6.97 x 10 ⁻⁵ or 0.697 x 10 ⁻⁴	2.53 x 10 ⁻³ or 25.3 x 10 ⁻⁴

FIGURE 5-3
WATER TRANSFER EFFICIENCY VS. AIR-WATER CONCENTRATION RATIO

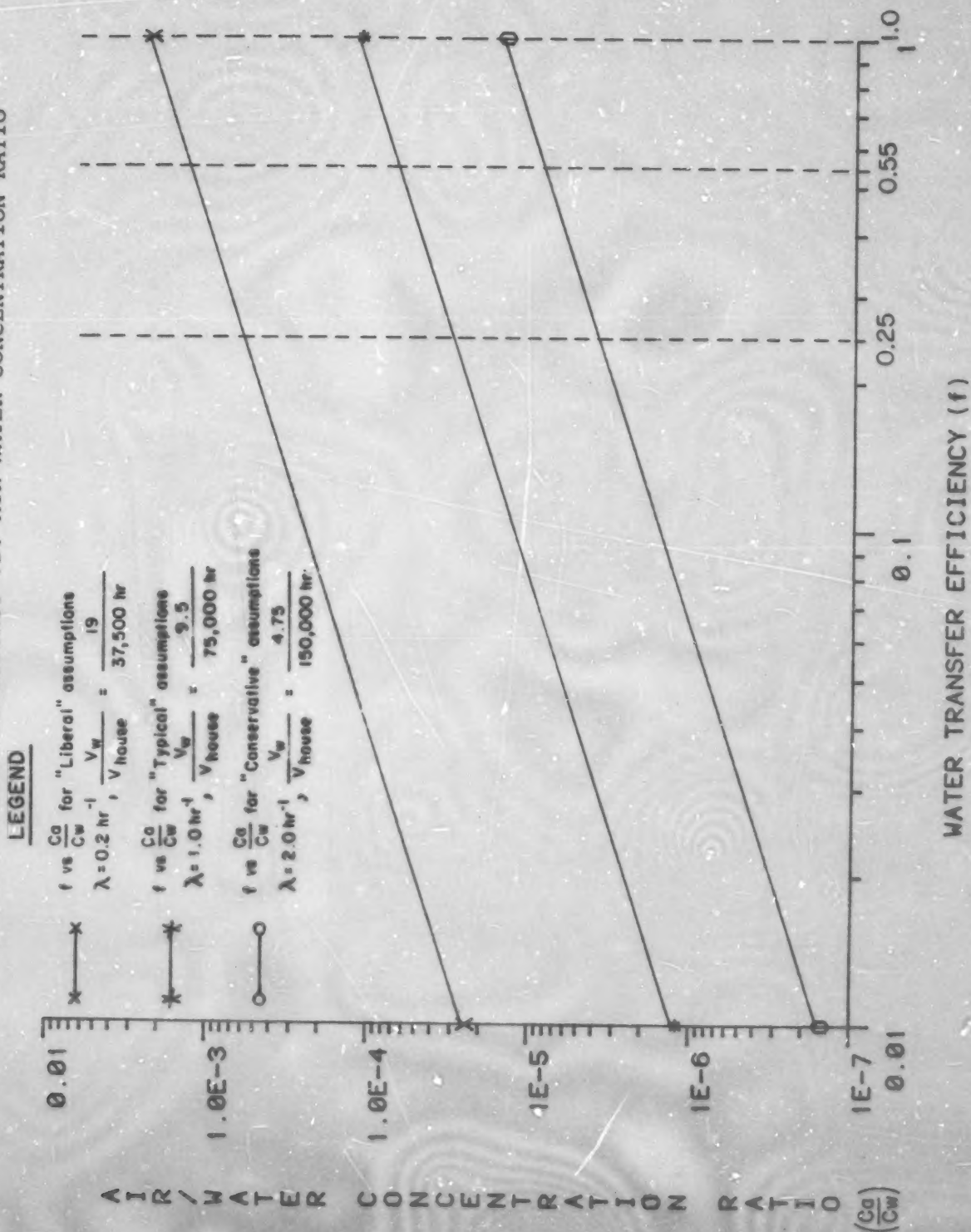
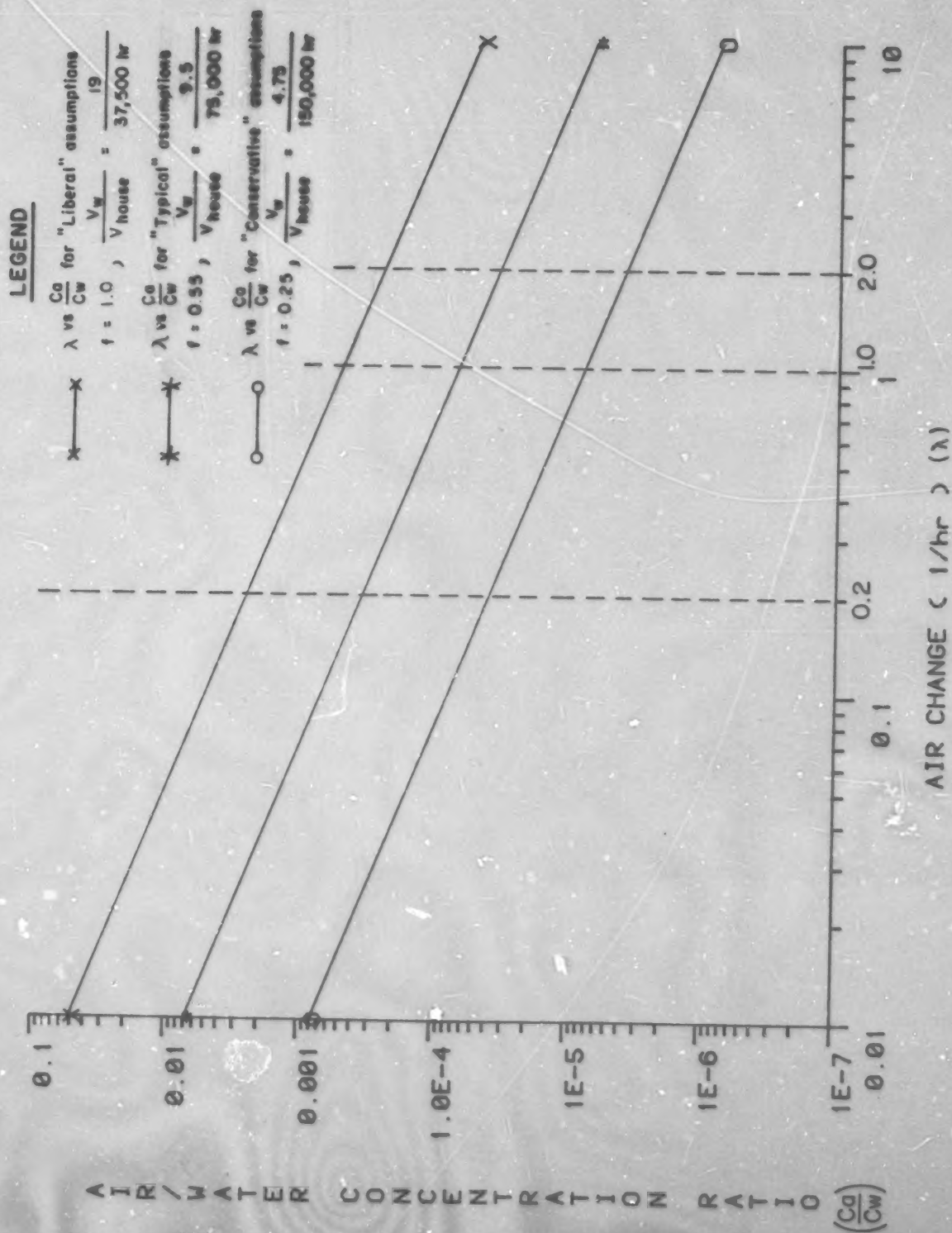


FIGURE 5-4

AIR CHANGE RATE VS. AIR-WATER CONCENTRATION RATIO



when the other variables are kept constant as shown in Table 5-5. Figure 5-5 illustrates the relationship between the C_a/C_w ratio for varying V_w/V_{house} when the other variables are kept constant as shown in Table 5-5. These results are tabulated in Table 5-6 and indicate that under liberal conditions, the C_a/C_w ratio varies from 1.59×10^{-4} to 25.3×10^{-4} , under typical conditions from 0.17×10^{-4} to 3.48×10^{-4} , and under conservative conditions, from 0.04×10^{-4} to 0.63×10^{-4} . Thus, depending upon the conditions that exist in a house, the C_a/C_w ratio should fall between the conservative and liberal values just outlined.

Limited data is available in the literature that relates the C_a/C_w ratio to the other major variables. This data is summarized in Table 5-7 and graphically displayed in Figures 5-6 through 5-8. These graphs indicate that actual data closely approximates the typical assumption plots and that all data falls within the boundary conditions established by the liberal and conservative assumptions.

Data based on other investigators' assumptions is summarized in Table 5-8 and graphically displayed in Figures 5-9 through 5-11. These graphs illustrate the close correspondence between our predictions and other investigators' predictions.

Thus, although one empirical number cannot be selected as the water-air diffusion factor, a range of numbers can be defined based on reasonable boundary conditions. This range has been shown to vary from 0.17×10^{-4} to 3.48×10^{-4} under typical conditions.

Kusuda (Ku80) developed a computer program to predict indoor radiation levels due to radon daughters at low building ventilation and air leakage rates. Data from this article is summarized in Figures 5-12 through 5-15. The terms working level, water transfer efficiency, and air change rate have previously been defined. The source strength (pCi/l/min) of a home when the radon in the potable water is the major source can be calculated as follows:

FIGURE 5-5
 V_w/V_{house} VS. AIR-WATER CONCENTRATION RATIO

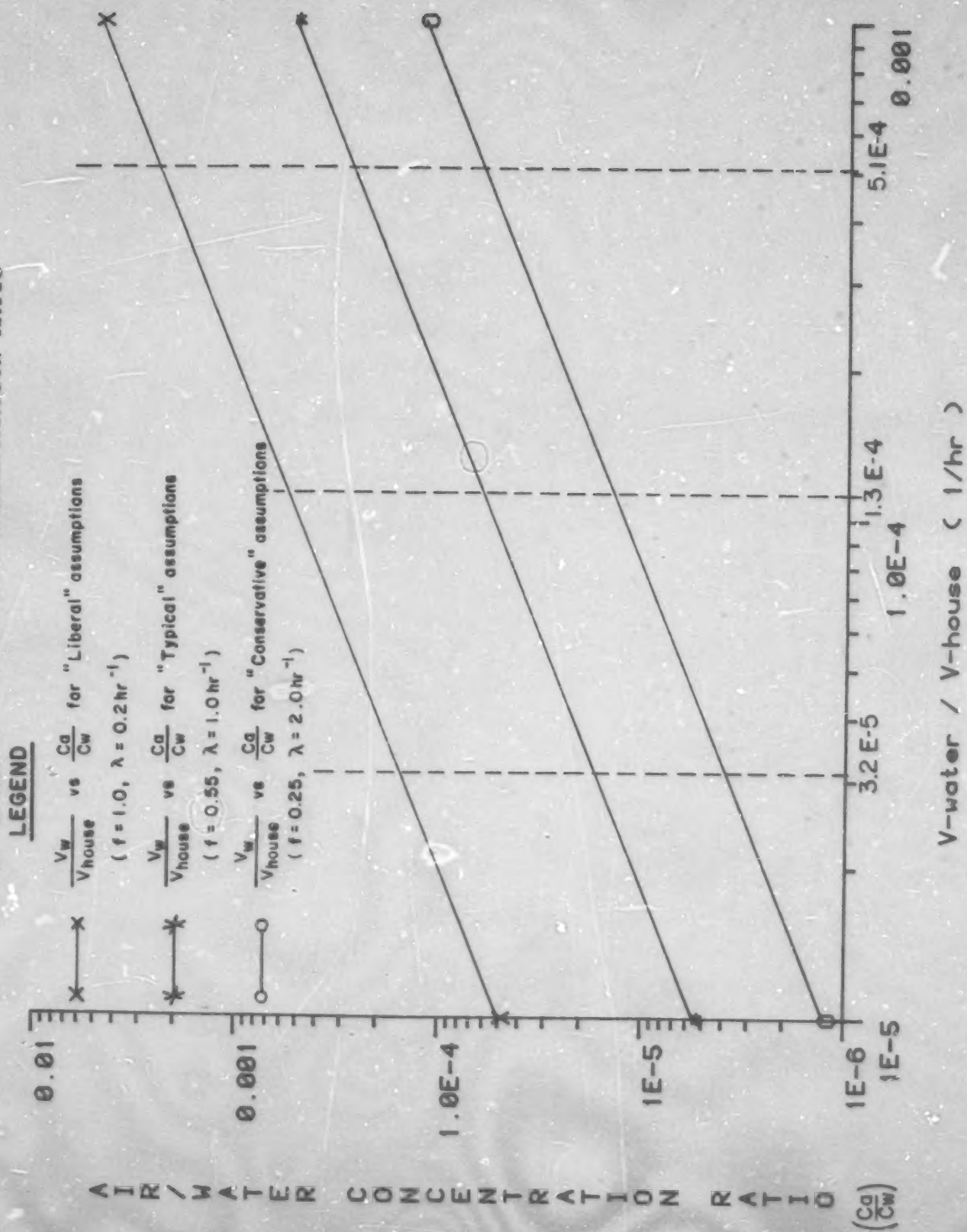


TABLE 5-6
C₂/C_w VARIABILITY

	C ₂ /C _w VARIABILITY		V/V _{house} =
	$f = 0.25 - 1.0$	$\lambda = 0.2 - 2.0$	
Liberal assumptions	$5.07 \times 10^{-4} - 2.53 \times 10^{-3}$	$2.52 \times 10^{-4} - 2.52 \times 10^{-3}$	$3.17 \times 10^{-5} - 5.07 \times 10^{-4}$ $1.59 \times 10^{-4} - 2.53 \times 10^{-3}$
Typical	$3.17 \times 10^{-5} - 1.27 \times 10^{-4}$	$3.48 \times 10^{-5} - 3.48 \times 10^{-4}$	$1.74 \times 10^{-5} - 2.79 \times 10^{-4}$
Conservative	$3.96 \times 10^{-6} - 1.58 \times 10^{-5}$	$3.96 \times 10^{-6} - 3.96 \times 10^{-5}$	$3.96 \times 10^{-6} - 6.34 \times 10^{-5}$

TABLE 5-7
ACTUAL DATA ILLUSTRATING THE RELATIONSHIP BETWEEN
THE AIR-TO-WATER CONCENTRATION RATIO AND OTHER MAJOR VARIABLES

Source	No. of Occupants	λ (hr ⁻¹)	f	V_w (l/hr)	V_{house} (l)	Actual Ca/Cw	Predicted (eq 2) Ca/Cw
Ge80	4	0.25	0.52	37.1	175,000	2.0×10^{-4}	4.4×10^{-4}
	4	1.0	0.52	37.1	340,000	0.57×10^{-4}	0.57×10^{-4}
	3	0.5	0.52	27.8	340,000	0.90×10^{-4}	0.85×10^{-4}
	5	1.0	0.52	46.4	500,000	0.50×10^{-4}	0.48×10^{-4}
He81	4	2.0				0.37×10^{-4}	
	3	0.5				1.0×10^{-4}	
	4	0.5				1.19×10^{-4}	
	2	0.5				1.08×10^{-4}	
	3	0.5				$<1.8 \times 10^{-4}$	
	2	0.4				1.61×10^{-4}	
He83	5	0.3				1.67×10^{-4}	
		1.0				0.8×10^{-4}	
He79		3.0				$(4 + 2) \times 10^{-5}$	
		1.1				$(1.8 + 0.5) \times 10^{-3}$	
		1.0				$(4.2 \pm 0.6) \times 10^{-4}$	
		2.1				4.5×10^{-5}	

FIGURE 5-6

ACTUAL DATA^a ILLUSTRATING THE RELATIONSHIP
BETWEEN THE AIR-WATER CONCENTRATION RATIO
AND AIR CHANGE RATE

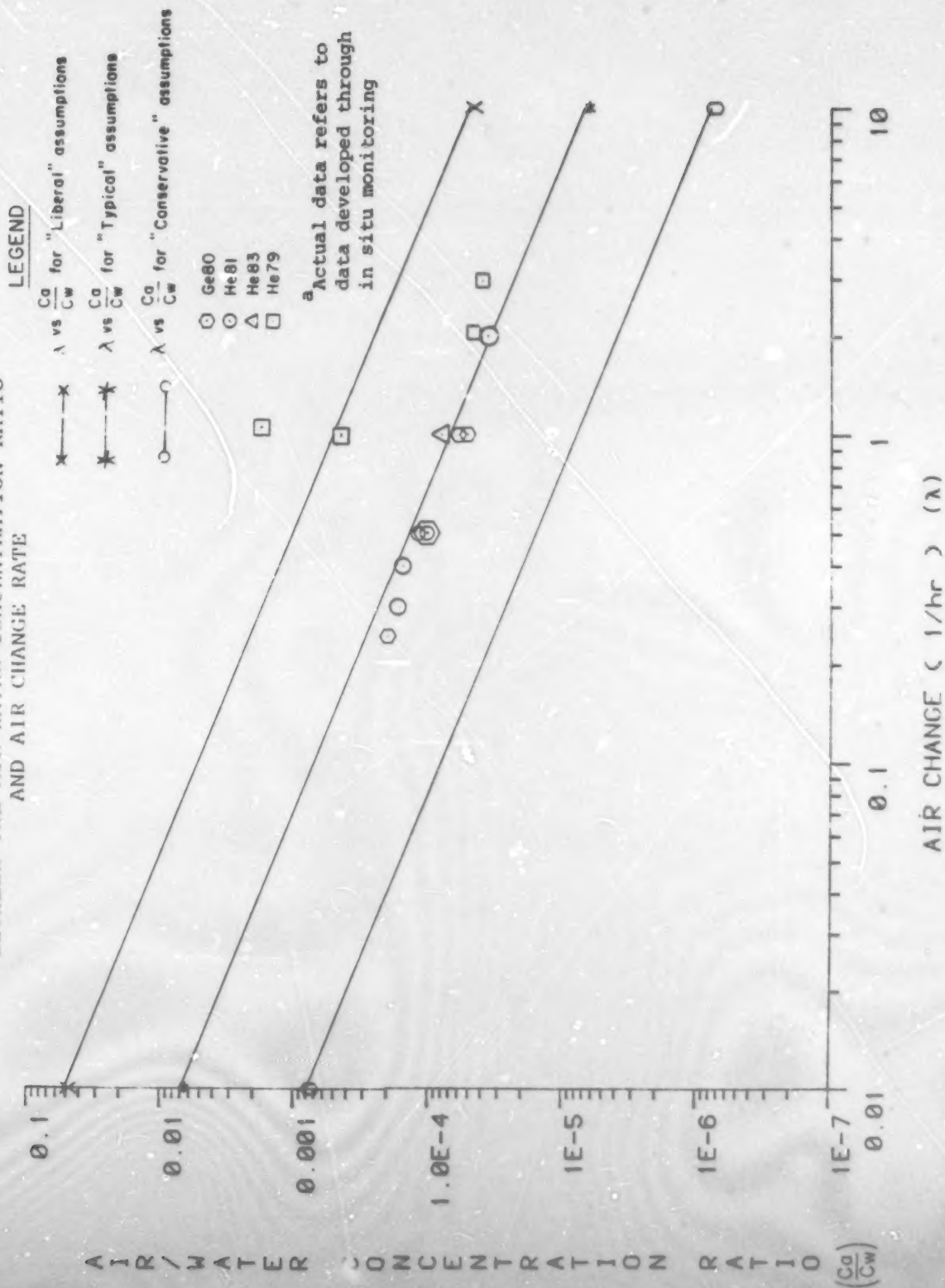


FIGURE 5-7
 ACTUAL DATA^a ILLUSTRATING THE RELATIONSHIP
 BETWEEN THE AIR-WATER CONCENTRATION RATIO
 AND WATER TRANSFER EFFICIENCY

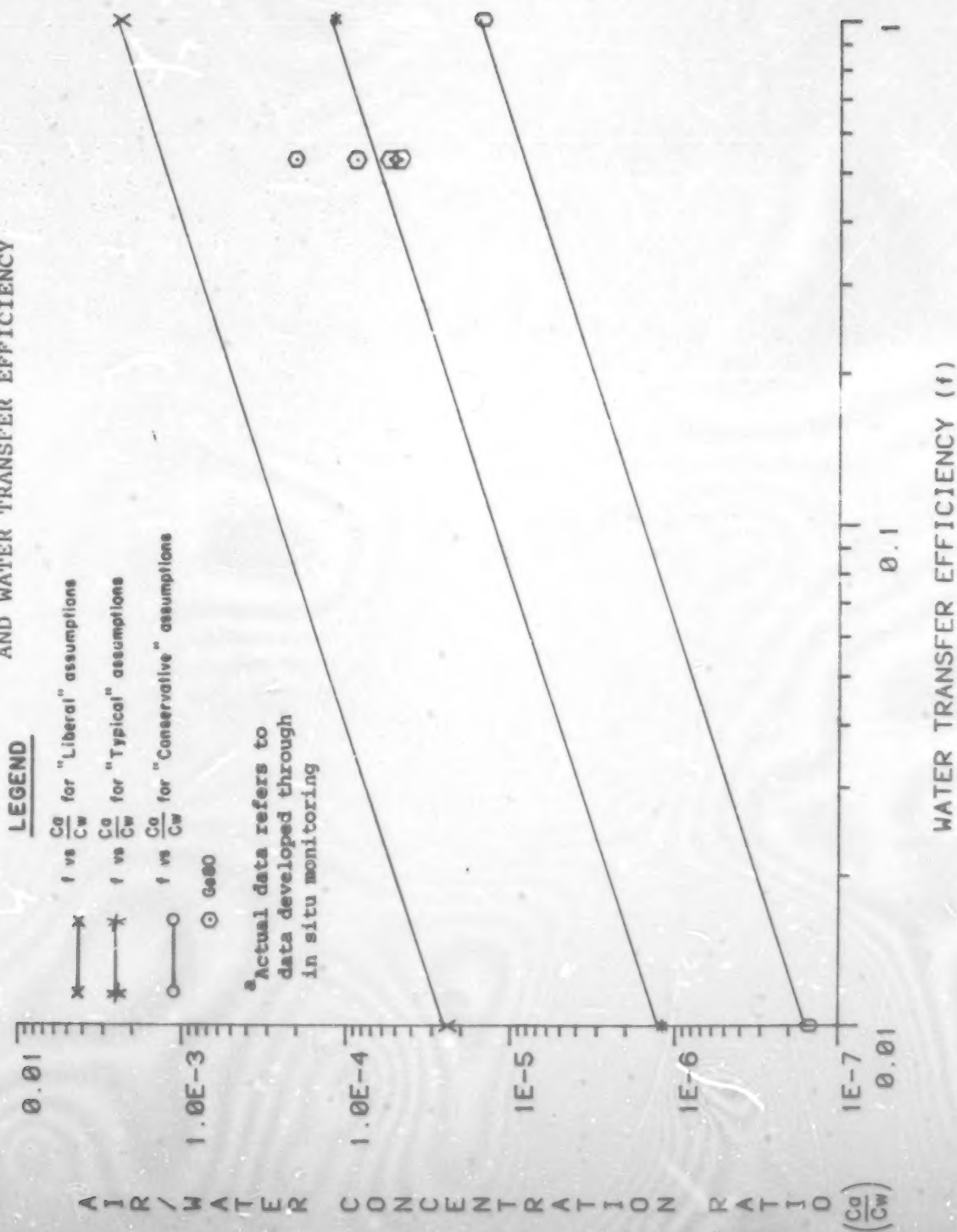


FIGURE 5-8

ACTUAL DATA^a ILLUSTRATING THE RELATIONSHIP
BETWEEN THE AIR-WATER CONCENTRATION RATIO
AND V_w/V_{house} RATIO

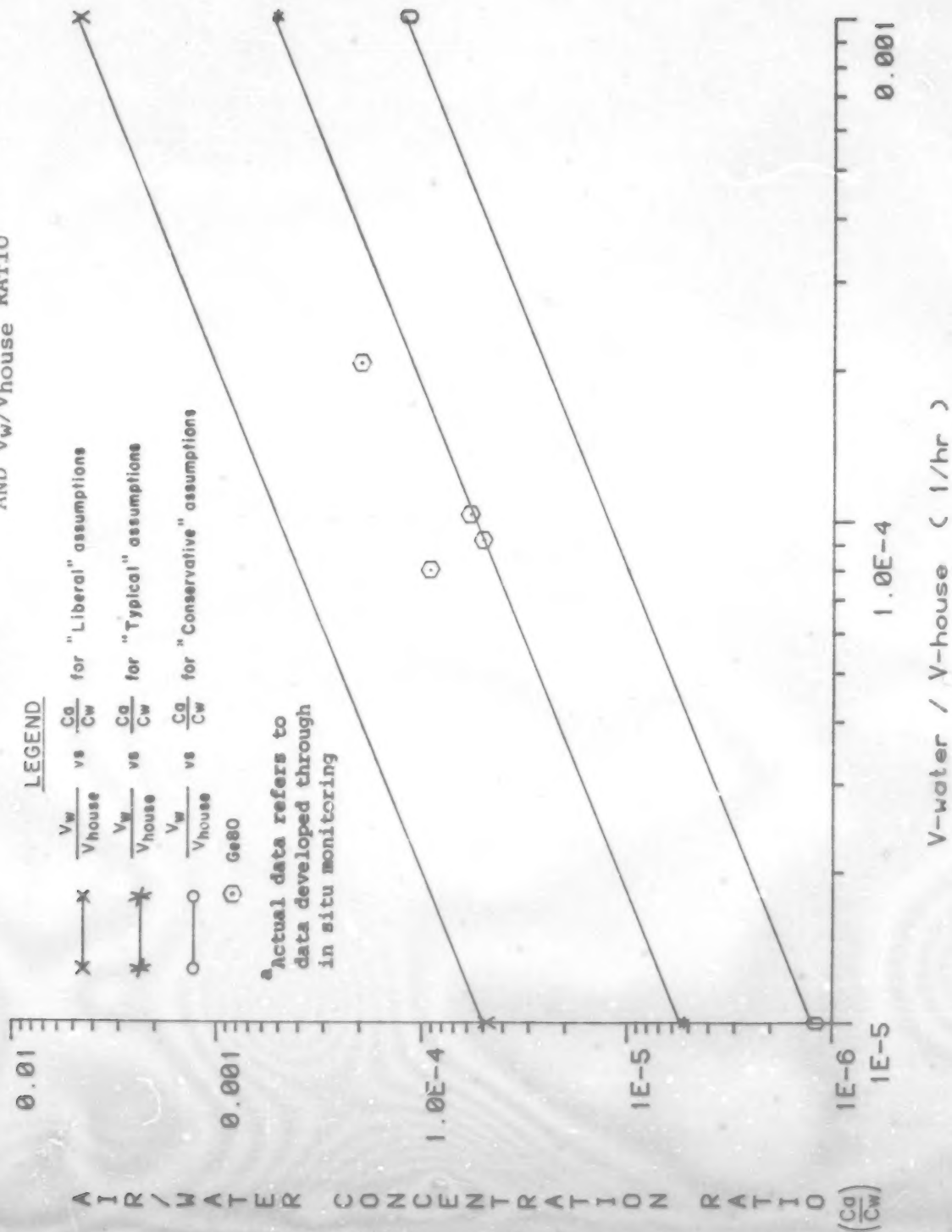


TABLE 5-8
LITERATURE DATA ILLUSTRATING THE RELATIONSHIP BETWEEN
THE AIR-TO-WATER CONCENTRATION RATIO AND ASSUMED MAJOR VARIABLES

Source	No. of Occupants	λ (hr ⁻¹)	f	V_w (l/hr)	V_{house} (l)	Predicted (eq. 2) Ca/Cw
Un77	4	1.0	1.0	41.7	230,000	1.8×10^{-4}
Pa79	4	2.0	0.625	23.3	400,000	1.8×10^{-5}
	4	1.0	0.625	23.3	400,000	3.6×10^{-5}
	4	0.5	0.625	23.3	400,000	7.2×10^{-5}
	4	0.25	0.625	23.3	400,000	1.4×10^{-4}
	4	1.0	0.625	23.3	140,000	1.0×10^{-4}
	4	1.0	0.625	23.3	330,000	4.4×10^{-5}
	4	1.0	0.625	23.3	660,000	2.2×10^{-5}
Ge80, Ge75		1.0			200,000	1.0×10^{-4}
Ge80		0.25	0.52	37.1	150,000	5.1×10^{-4}
		0.50	0.52	37.1	340,000	1.1×10^{-4}
		1.0	0.52	37.1	340,000	0.57×10^{-4}
		2.0	0.52	37.1	680,000	0.14×10^{-4}
He82		1.0				0.8×10^{-4}

FIGURE 5-9

LITERATURE DATA ILLUSTRATING THE
RELATIONSHIP BETWEEN THE AIR-TO-
WATER CONCENTRATION RATIO AND
AIR CHANGE RATE

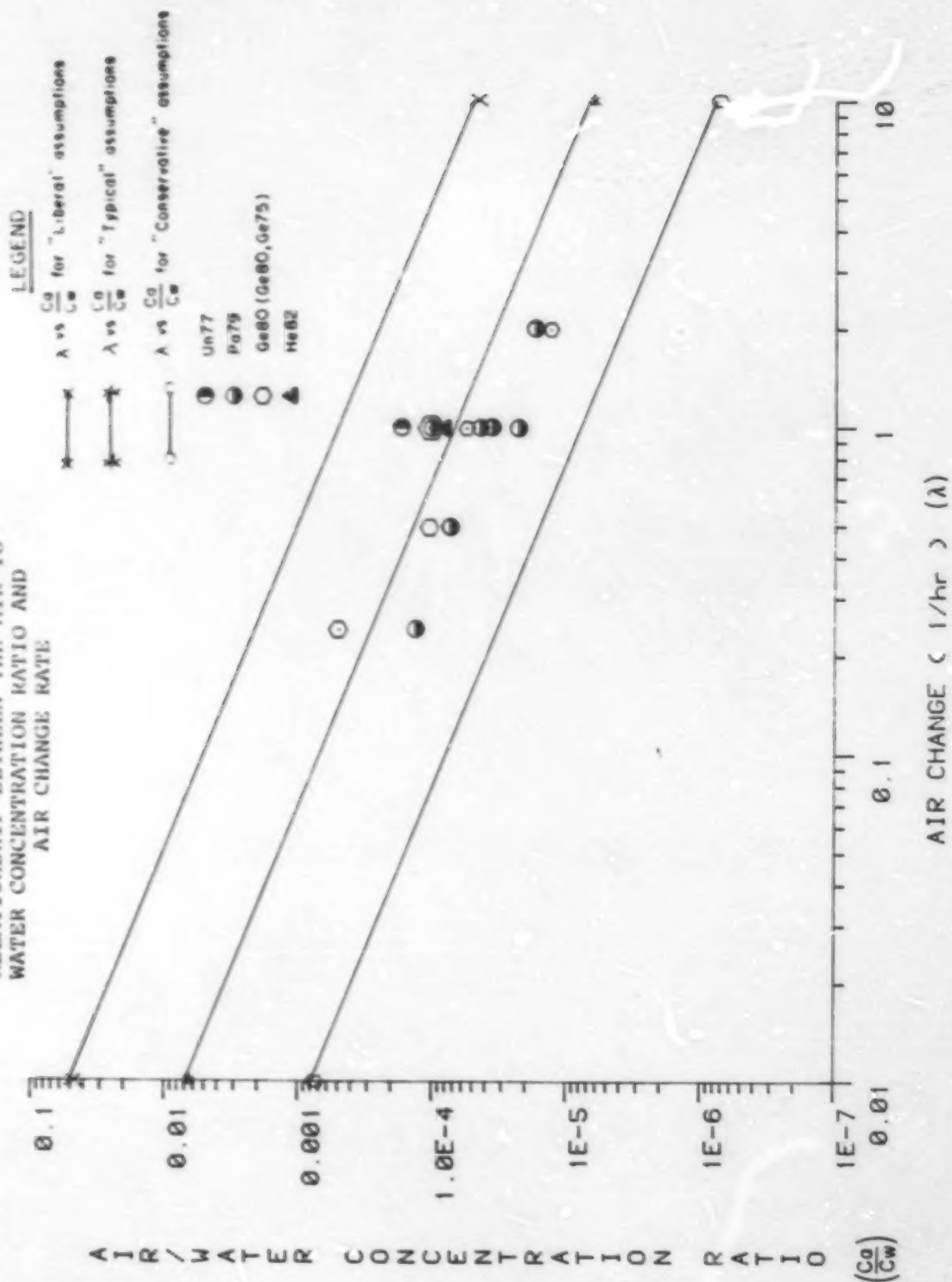


FIGURE 5-10
LITERATURE DATA ILLUSTRATING THE
RELATIONSHIP BETWEEN THE AIR-TO-
WATER CONCENTRATION RATIO AND
WATER TRANSFER EFFICIENCY

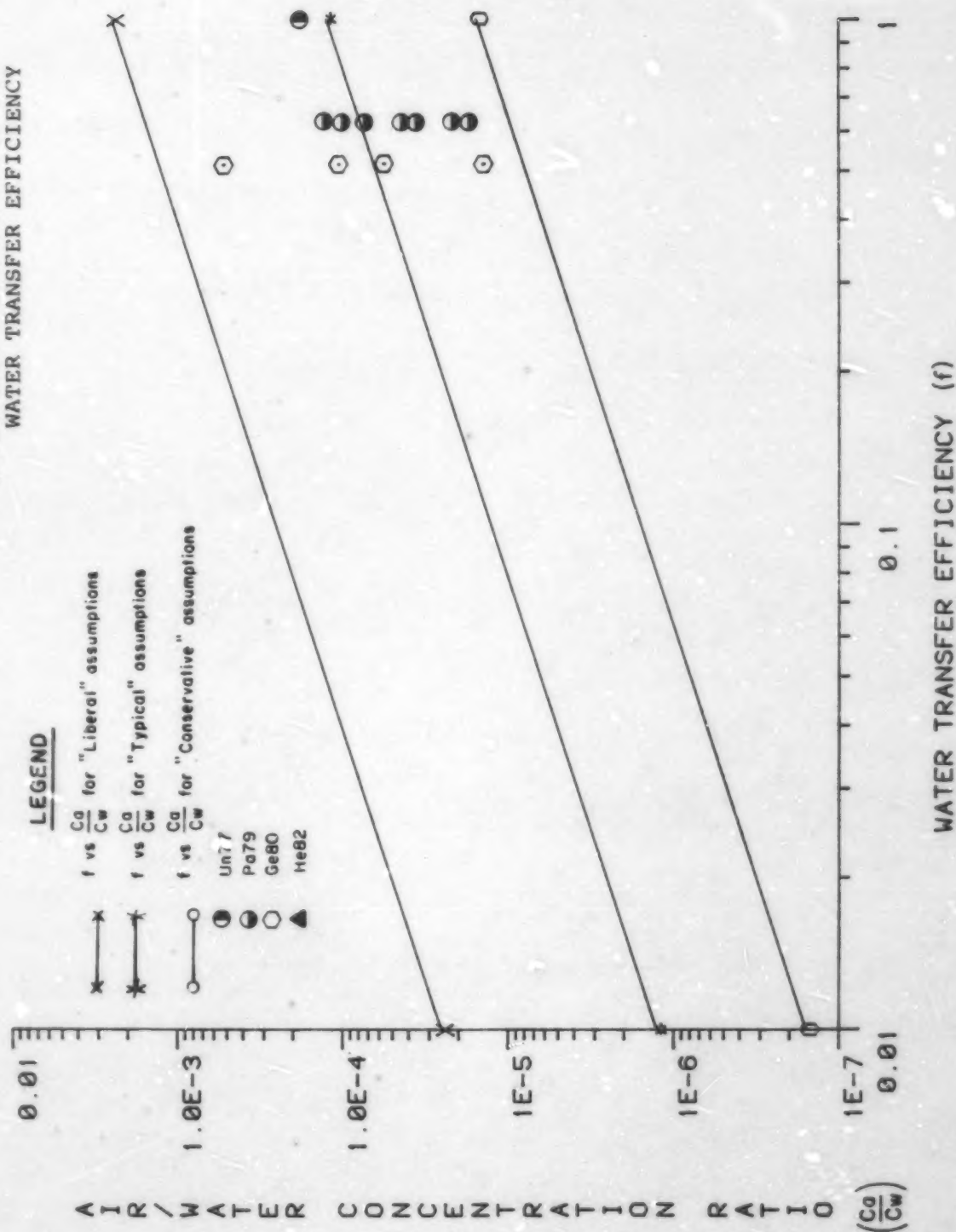


FIGURE 5-11

LITERATURE DATA ILLUSTRATING THE
RELATIONSHIP BETWEEN THE AIR-TO-
WATER CONCENTRATION RATIO AND
 V_w/V_{house} RATIO

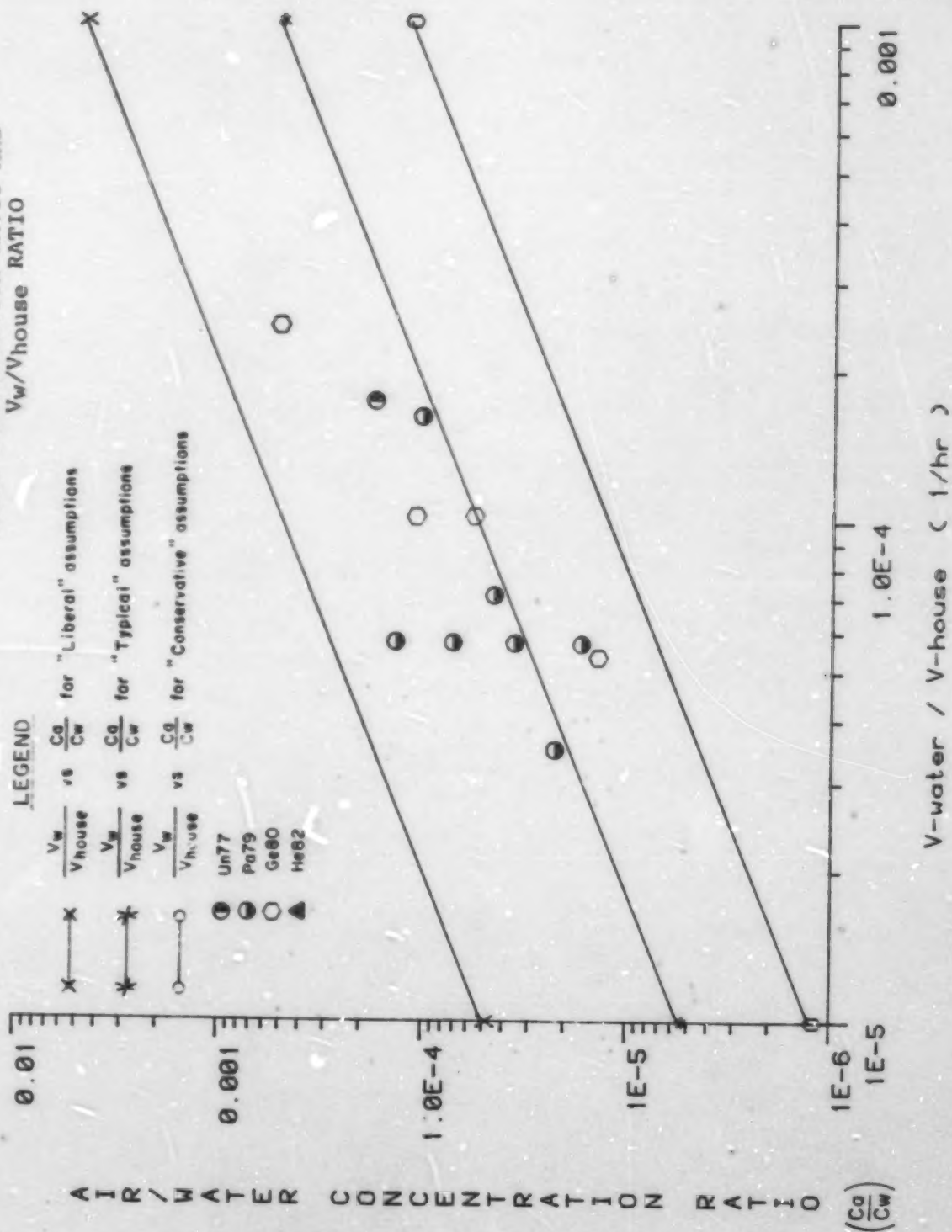


FIGURE 5-12
WORKING LEVEL VS. AIR CHANGE RATE

Source Strength = 0.01 pCi/l/min
Outdoor Radon Conc. = 0.2 pCi/l
Outdoor Equilibrium Factor = 0.6
Ca Init. = 0.2 pCi/l

(Adapted from Source Ku80)

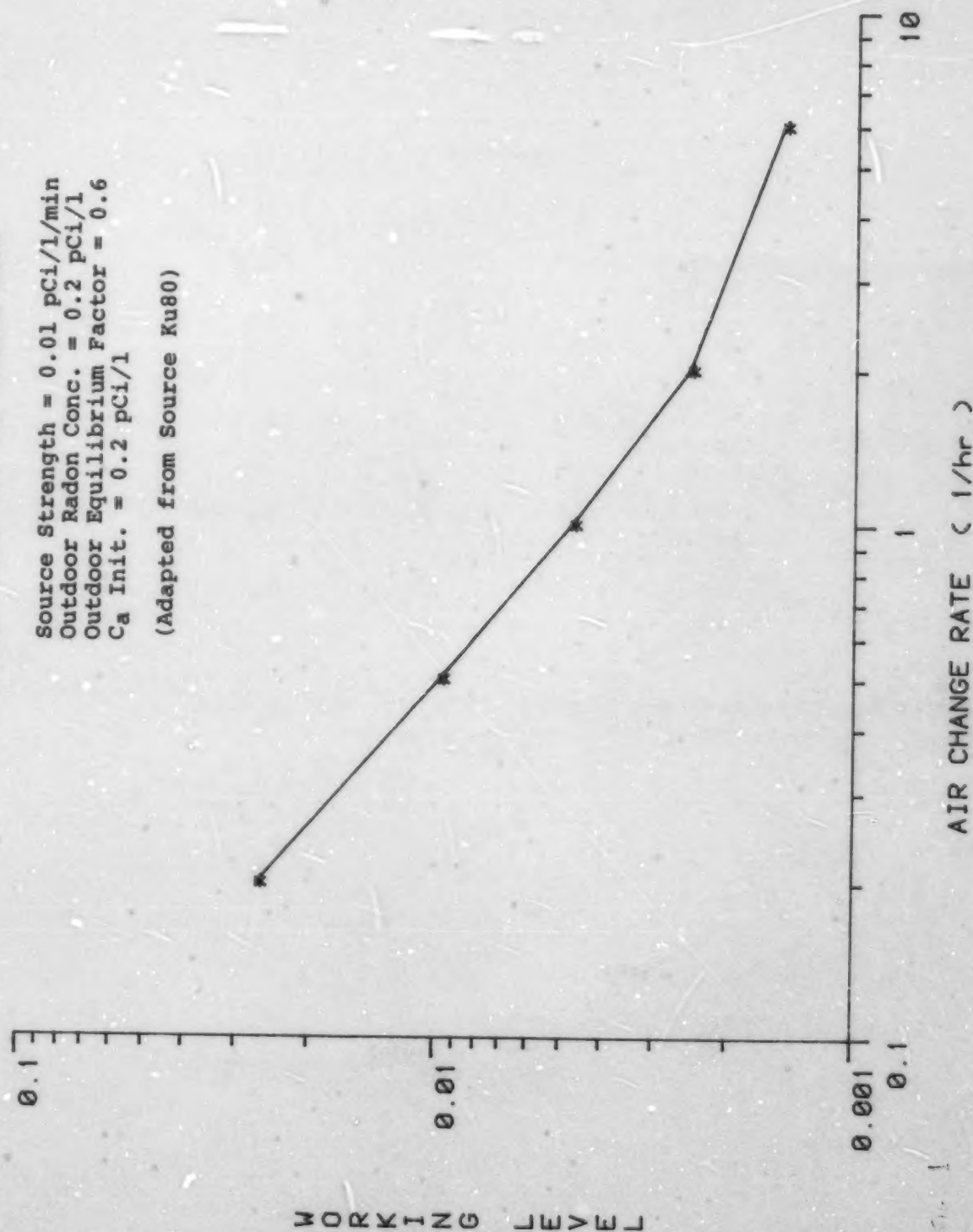


FIGURE 5-13
WORKING LEVEL VS. AIR CHANGE RATE

Source Strength = 0.01 pCi/l/min
Outdoor Radon Conc. = 0 pCi/l
 C_a Init. = 0 pCi/l

(Adapted from Source Ku80)

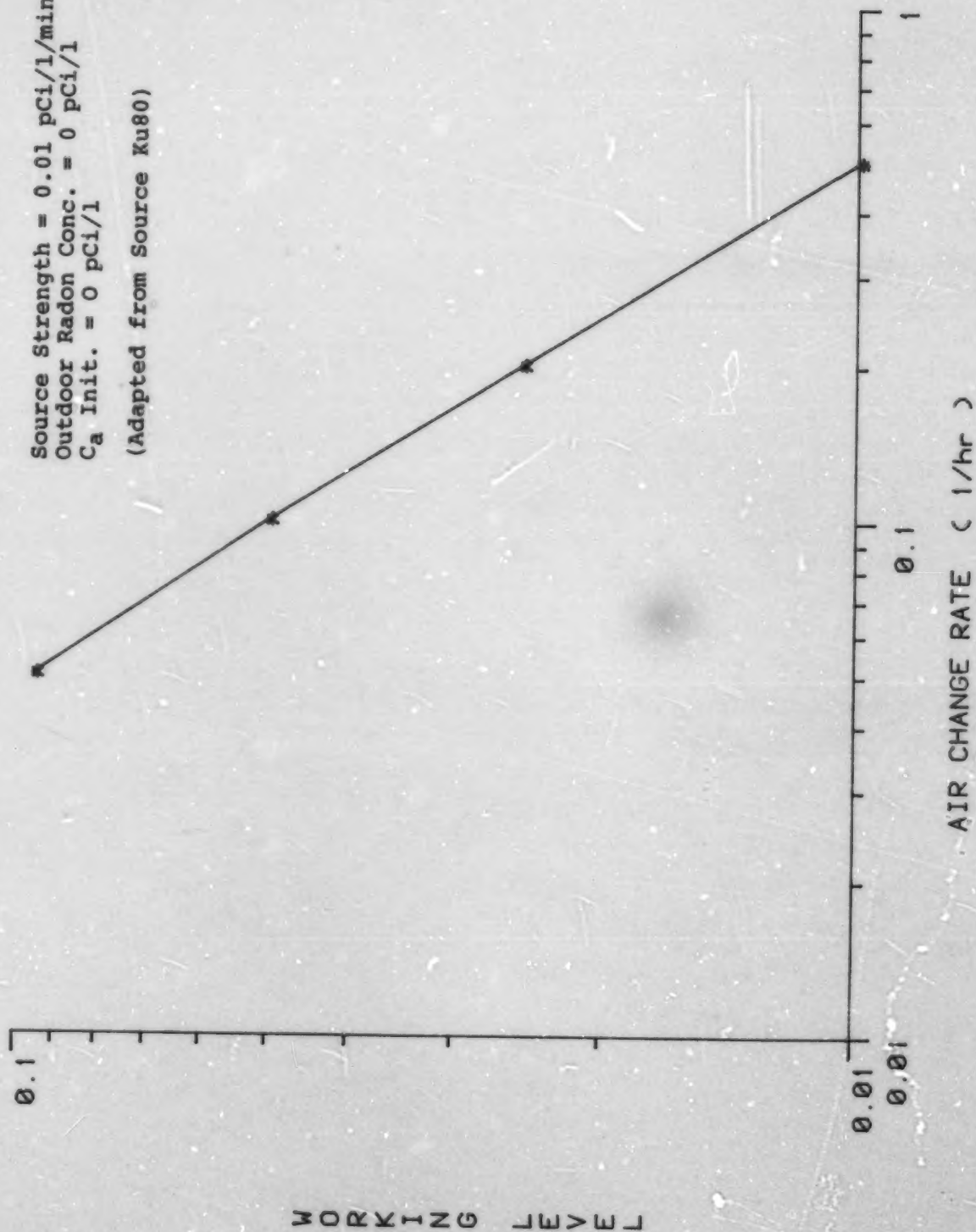
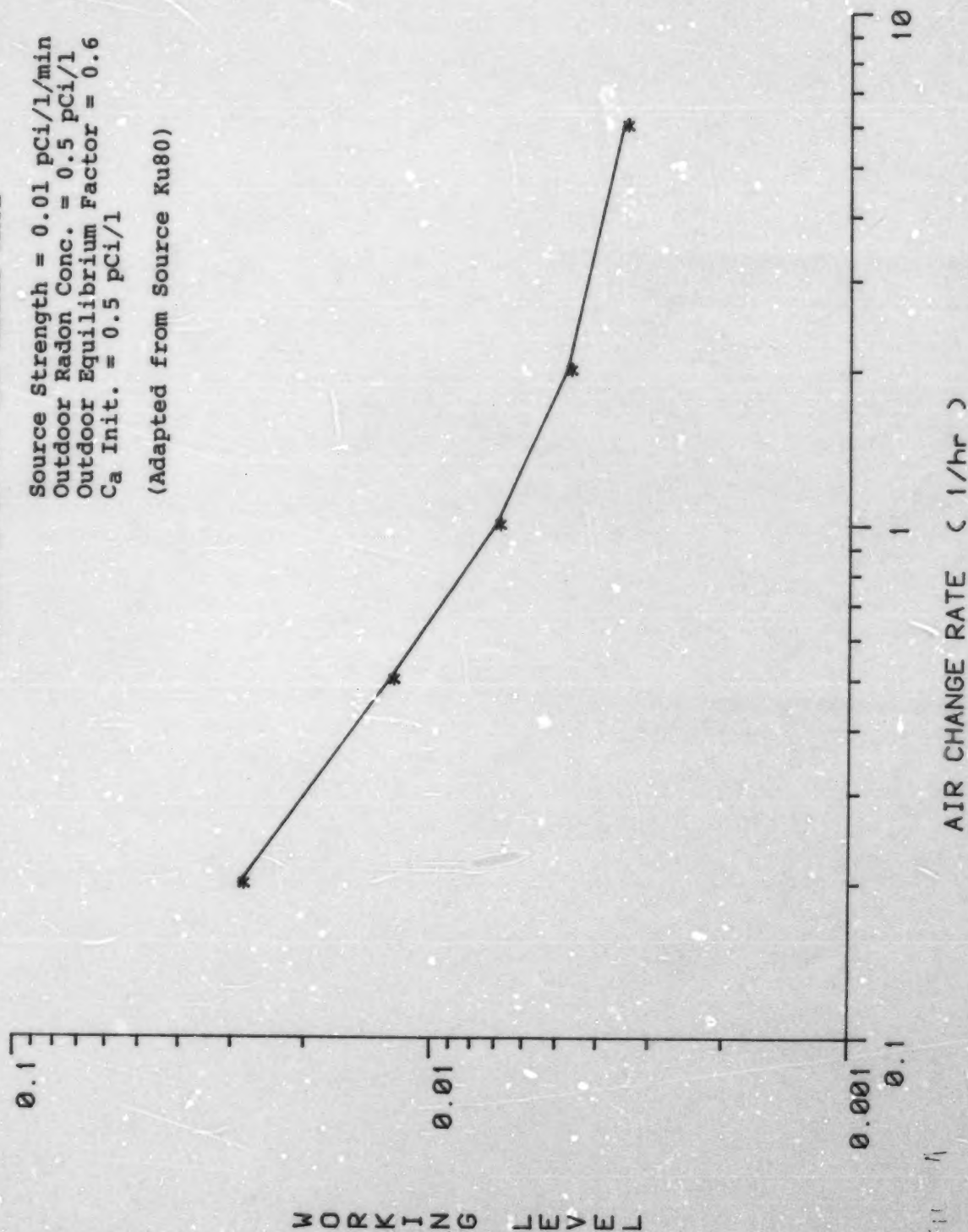


FIGURE 5-14

WORKING LEVEL VS. AIR CHANGE RATE

Source Strength = 0.01 pCi/l/min
 Outdoor Radon Conc. = 0.5 pCi/l
 Outdoor Equilibrium Factor = 0.6
 C_a Init. = 0.5 pCi/l

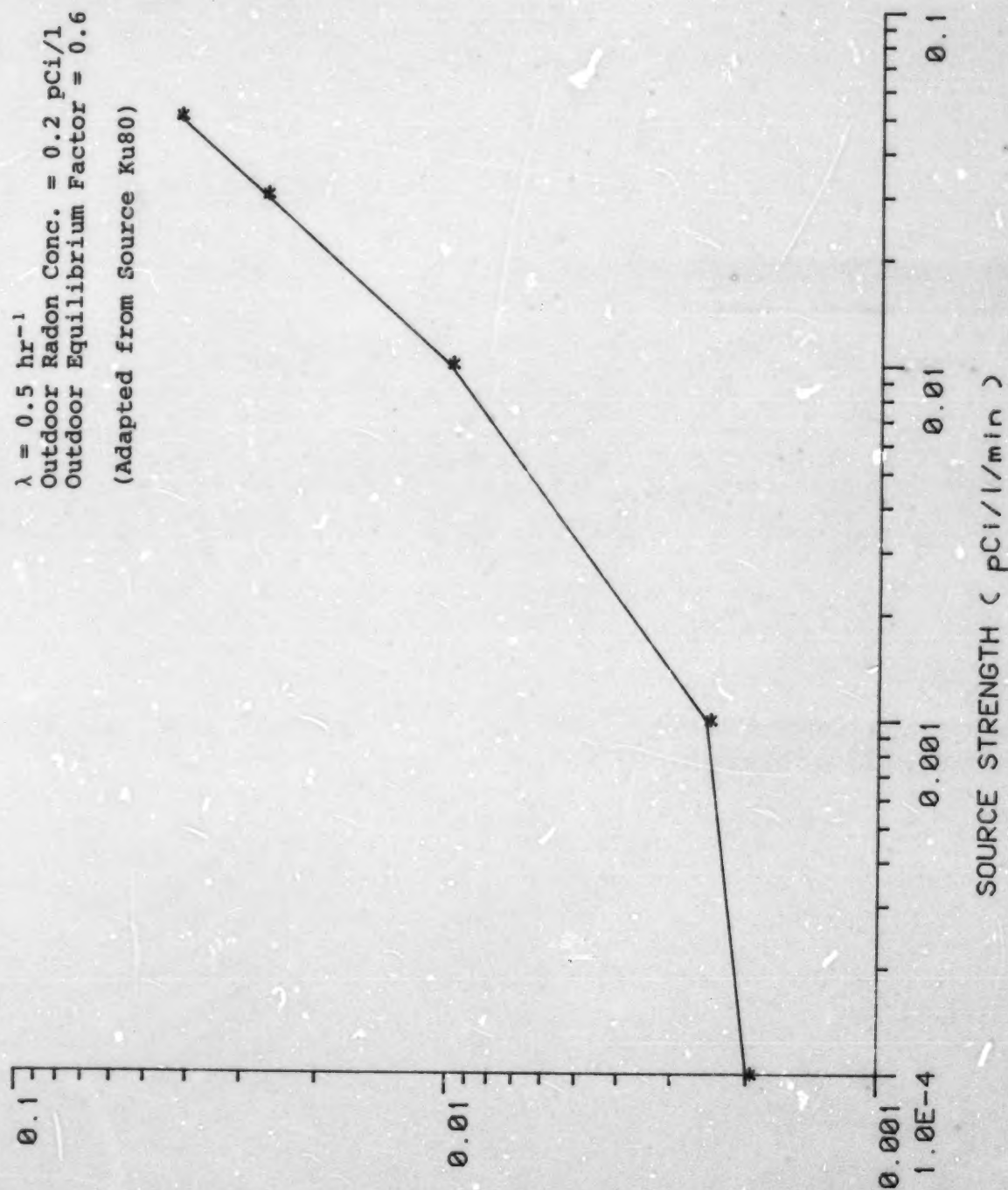
(Adapted from Source Ku80)



WORKING LEVEL

FIGURE 5-15
WORK LEVEL VS. SOURCE STRENGTH

$\lambda = 0.5 \text{ hr}^{-1}$
Outdoor Radon Conc. = 0.2 pCi/l
Outdoor Equilibrium Factor = 0.6
(Adapted from Source Ku80)



Basis: $C_w = 10,000 \text{ pCi/l}$
 $V_w = 9.5 \text{ liters/hr/person}$
 $V_{\text{house}} = 75,000 \text{ liters/person}$
 $f = 0.55$

$$\begin{aligned} \text{Average Source Strength} &= \frac{(10,000 \text{ pCi/l})(9.5 \text{ l/hr/person})(\text{hr}/60 \text{ min})(0.55)}{(75,000 \text{ liters/person})} \\ &= 0.012 \text{ pCi/l/min} \end{aligned}$$

Figure 5-12 illustrates the potential alpha energy concentration's (WL units) dependency on air change rates from 0.2 to 6.0 air changes/hr for a source strength of 0.01 pCi/l/min and an initial indoor air radon concentration of 0.2 pCi/l. Figure 5-13 shows the effects of even lower air change rates (outdoor radon levels neglected here) on household air WLs. Figure 5-14 is similar to Figure 5-10, except the outdoor radon concentration was raised to 0.5 pCi/l from 0.2 pCi/l, resulting in a uniform increase in the household WLs. Figure 5-15 shows the dependence of the potential alpha energy concentration (WL) on the source strength. A fixed air change rate of 0.5 hr⁻¹ was used in this calculation.

6.0 CONTROL TECHNOLOGY

This chapter presents and discusses the various control technologies that are available for the removal of radon from water sources and also for the control of indoor radon concentrations after entering the home. An evaluation is made of the cost, efficiency and applicability of each control technology where sufficient information is available.

6.1 REMOVAL OF RADON FROM WATER SOURCES

There are currently three methods that can be used to reduce the level of radon in potable water supplies: aeration, granular activated carbon adsorption, and decay. Simple decay as a removal method is considered impractical because of the length of time water would have to be stored before adequate radon removals take place. Since radon has a half-life of 3.823 days, a typical household would have to store its water supply for 19 to 31 days to achieve radon removals of 96.9 to 99.6 percent. Based on a water usage of 9.5 liters/hr/person, a two-member household would need around an 8,700 liter storage tank to achieve 97 percent radon removal, and the tank would have to be constructed in multiple compartments to avoid backmixing of treated water with untreated water. The size of this equipment is considered impractical for normal domestic applications. The remainder of this section will therefore focus on the use of aeration and granular activated carbon adsorption for the removal of radon from potable water supplies.

Aeration is an effective treatment technology for the removal of radon gas from water because of the increased air-water interface created by the air bubbles. Large treatment plants generally either employ positive draft aerators or natural draft aerators. Positive draft aerators utilize forced air to remove entrained gases while natural draft aerators allow water to flow over trays or slabs without forced air flow through the system. Typical

household devices that reduce radon concentrations in the water include faucet aerators, faucet sprays, and the boiling of water. However, any removal method must also provide for the safe disposal of the radon liberated to the air.

Table 6-1 summarizes available literature on the use of aeration for radon removal from water. Depending on the aeration method used anywhere from 20 to 96 percent of the radon can be removed. This data summary indicates that radon removal seems to occur best for high surface area methods or with spray at room pressure or lowered pressure.

Granular activated carbon removes contaminants in water by the process of adsorption or the attraction and accumulation of one substance on the surface of another. In general, the sorption capacity of an activated carbon is related to its high internal surface area and pore structure. Granular activated carbons typically have surface areas ranging from 500 to 1,400 square meters per gram (m^2/g) (EPA73). The tremendous internal surface area is the main characteristic that enables activated carbon to be so effective in removing impurities from water.

Available literature on the removal of radon using activated carbon is also summarized in Table 6-1. In an experimental unit, a 63 percent radon removal efficiency was noted for an influent stream containing 90,000 pCi/l of activity (He81). A removal efficiency of 63 percent is rather low for a GAC unit. This low removal is probably due to the fact that this was only an experimental column run in which column operating conditions would not be optimal. Commercial units developed for household use should exhibit better performance. Another study summarized the performance of 13 household GAC units containing anywhere from 0.03 to 0.07 m^3 of activated carbon. Radon removal efficiencies for these units ranged from 62.1 to 99.8 percent with an average removal of 92.5 percent (Lo83).

TABLE 6-1
TREATMENT TECHNOLOGY RADON REMOVAL FROM WATER SUPPLIES

Current Source	Aeration		Granular Activated Carbon	
	Description	Radon Removal (%)	Description	Radon Removal (%)
He79	Bubbling method without low pressure	20-30		
He79	Aeration followed by degassing by fine spray at low pressures	70		
He81	Coarse bubble diffused aeration vessel - 1/2 radon removal after 1 hour: Air Flow Rate SCFH		GAC Experiment - Influent radon concentration = 90,000 pCi/l	63
		12		
		15		
		30		
Sm61	Household Devices: Faucet aerator Faucet spray Boiling (1-5 minutes)	48-56 17-18 95-100		
	Treatment Plants: Wooden - slot aerators Wooden - trough spray-type aerator	77 68		
Ho83	Positive Draft Aerators Natural Draft Aerators	78-96 (avg. 86) 33-73 (avg. 57)		
Lo83			Field performance of 13 household GAC systems	62.1-99.8 (avg. 92.5)
La83	Aeration - 132 to 151 liter diffused aeration tank	93-95	Carbon adsorption	96

Experimental findings and GAC unit field performance indicate that once a steady-state operation has been achieved, adsorption equals decay, and radon does not increase to a higher level in the bed.

The cost of a household GAC unit essentially involves only the initial purchase cost. The cost of commercially available GAC units ranges from \$500 to \$800 for 0.03 to 0.07 m³ units, respectively. These size units would be adequate for radon removal from mid-range radon laden potable water and are comparable in price to GAC units capable of purifying 760 liters per day of potable water with a radon concentration of 30,000 pCi/l or less (La83). Operation cost is almost zero, with only a minor cost of pumping extra water for infrequent backwashing. Maintenance cost is also very low and is comprised of periodic makeup carbon to replace GAC lost in backwashing. The maintenance cost is estimated to average less than \$10 per year over the life of the unit (Lo83).

One drawback to the use of GAC is that suspended solids build-up or algae growth can blind the carbon. If water is being treated that contains high suspended solids concentrations, a filtration system may have to be installed before the GAC unit or frequent backwashing may be required. This fact must be considered when selecting a system.

A summary of factors that influence the radon efficiencies of a GAC unit follow.

- 1) GAC adsorption units must be sized according to the daily mass loading of radon. Thus, the concentration of radon in the potable water and the family's water usage determine the GAC unit's size. A unit that is undersized for a family's needs will have poor radon removals.

- 2) A study performed by Lowry (Lo83) indicated that the type of activated carbon used does affect the radon removal efficiency. In limited laboratory adsorption isotherm testing, HydroDarco 4000 GAC

TABLE 6-2

SUMMARY OF PERFORMANCE AND ECONOMICS OF
DIFFUSED AERATION AND GRANULAR ACTIVATED CARBON TO
REMOVE RADON FROM WATER FOR HOUSEHOLD USE (750 l/day DEMAND)

Influent Rn (pCi/l)	Effluent Rn (Estimated) (pCi/l)		Cost (Estimated) ^a	
	GAC	Aeration	Capital GAC	Annual Operating Cost GAC Aeration
15,000	1350-3300	750	\$431-757	\$19 \$60
30,000	2700-6600	1500	\$431-757	\$19 \$60
150,000	1200 (2)	<7500	\$1,500	\$1,000 \$40 \$80

^a Not specifically stated in article, but assumed to be 1983 dollars.

Source: (La83)

was proven superior to Fitratorb-300 (Calgon), Nuchar WV-W (Westvaco), Nuchar WV-L, Nuchar WV-G, and Witco 950 (Witco Chemical). A comparison has not been made in field installations. In cases where another unknown brand of GAC was used in place of HydroDarco, it appears that removal efficiency was reduced by approximately 10 percent (Lo83). However, this reduced removal efficiency cannot be directly attributable to the type of GAC, as other variables also affect removal efficiencies.

Table 6-2 summarizes the performance and economics of Diffused Aeration and Granular Activated Carbon to remove radon from potable water for household use. This data indicates that the capital cost of GAC and aeration are about the same but GAC is less expensive to operate.

A comparison of aeration versus carbon adsorption for the removal of radon from potable water supplies once the water has reached the residence leads to the following conclusions.

- 1) Radon removal using aeration is highly variable and removal efficiencies are highly dependent on the system's ability to de-gas the radon once aeration has taken place.
- 2) Aeration of potable water in the home would have to be done in an isolated well ventilated area to adequately disperse out-gassed radon outdoors.
- 3) The initial capital cost, operating cost and maintenance of an aeration system would be higher than an activated carbon system because of the use of motors and compressors. The cost advantage of GAC over aeration appears to hold true particularly for low to moderate influent ^{222}Rn concentrations ($<50,000$ pCi/l).
- 4) Carbon adsorption has more consistent and efficient removal efficiencies. Literature sources indicate that 62 to 99.8 percent of radon can be removed from water by carbon adsorption.

- 5) The operation of a carbon adsorption unit is much easier than an aeration system.

A comparison of aeration versus carbon adsorption for the removal of radon from potable water supplies at a municipal water treatment plant (MWTP), leads to the following conclusions:

- 1) In a MWTP, aeration takes place outdoors and out-gassed radon is adequately dispersed and undergoes significant dilution with ambient air.
- 2) Radon levels in the treated final effluent are highly dependent on the order of the treatment process. Even though efficient radon removal is achieved across a carbon adsorption unit or aerator, overall final radon concentrations across the entire treatment process may be higher than influent radon concentrations due to the buildup of radium in other treatment equipment. For example, it is possible that radium removed and trapped in iron removal filters or zeolite softeners could generate radon levels in finished water above the levels observed in the raw water (Ho83). Thus, the placement of the radon removal equipment in the overall water treatment process is of vital importance. Radon removal equipment must follow any treatment equipment that could generate radon if overall reductions in radon are to be achieved.

6.2 CONTROL OF INDOOR AIR CONCENTRATIONS

There are a variety of treatment technologies that can be used to reduce the concentration of radon in indoor air. Technologies evaluated include circulation, ventilation, filtration, charcoal adsorbers, chemical reaction and space charging. Treatment technology are evaluated for their ability to remove radon and/or radon progeny. Literature sources generally express radon concentrations in units of pCi/l. However, in the case of radon progeny a special unit of concentration is used, the working level (WL), based on the release of alpha particle energy from radon progeny. This term has previously been defined in Chapter 4.

6.2.1 Circulation

It is a documented fact that radon daughters attach rapidly or plateout on the surfaces (walls, ceilings, floors, equipment, etc.) of uranium mines (Ho57, Ho79b). The circulation of air in uranium mines has been used successfully to reduce WLs through enhanced radon progeny plateout.

This same technology, air circulation, has been evaluated to determine its usefulness for reducing WLs in the household environment. In the home, circulating fans are commonly employed to increase indoor air circulation. Some very interesting studies have been performed to evaluate this phenomena in the home.

Holub (Ho79b) evaluated the relationships between humidity, condensation nuclei concentration, turbulence and the plateout of radon progeny on surfaces. Results of this study are summarized as follows:

1) Increased plateout occurred when the condensation nuclei concentration became sufficiently low to maintain a large unattached daughter fraction. Once the condensation nuclei count rose to a relatively high level ($10^5/\text{cm}^3$), the WL rose and the wall background decayed to lower values, indicating attachment of the radon progeny to the aerosol particles, thus preventing wall plateout. Thus, the absence of aerosol particles increases the rate of radon daughter plateout.

2) In another experiment, an IMC Boxer fan (operating at 3,500 rpm) was used to circulate the air in a control chamber.

a) At low humidity (<5%), the operation of the fan was observed to reduce the WL in the chamber by 50 percent, and doubled the radon daughter activity on the fan blades. At the same time, the radon concentration, radon daughter activity on the walls, and condensation nuclei concentrations all remained constant. Thus, the action of the fan is to remove airborne radon daughter activity by deposition onto fan blades.

b) At high humidity (>80%), the WL and fan activity are unaffected by the fan motion. The presence of the water vapor apparently inhibits the attachment of the activity to the moving fan blades.

3) It was concluded that the high turbulence around a moving fan blade, coupled with the image force and high sticking coefficient, can cause substantial deposition of daughter activity onto the blades under conditions that permit the active species to retain a charge. At low humidity, the active species retains a charge. At high humidity (>80% R.H.), radon activity deposition onto the fan blade is inhibited, presumably by providing a mechanism for neutralization of the charge on the active ion and thus lowering its sticking coefficient.

4) No information was given on the effect of mid-range relative humidities (5-80% R.H.) on radon daughter plateout.

Hinds (Hi83) evaluated the performance of box and ceiling fans for WL reductions in an experimental control chamber. His results can be summarized as follows:

<u>Parameter</u>	<u>Box Fan</u>	<u>Ceiling Fan</u>
Flow Rate (m ³ /s)	2.6	3.3
Fan Effective Air Exchange Rate (hr ⁻¹)	120	152
Power (W)	185	155
WL Reduction (%)	63	58
Reduction in Attached Activity (%)	63	60
Reduction in Unattached Activity (%)	33	38
Infiltration Air Change Rate (hr ⁻¹)	0.52	0.52

The primary mechanism for the reduction in WL by air circulating fans was enhanced diffusive deposition to the chamber surfaces. Vigorous air circulation brought all parts of the chamber air close to the chamber surfaces, and thus facilitated molecular diffusion to the chamber surfaces. This deposition mechanism was confirmed by measuring activity deposited on targets placed on chamber surfaces. Less than 10 percent of the deposited activity was found attached to the fan blades.

These literature sources indicate that circulating fans can reduce WLs in household air by 50 to 63 percent. Circulating fans only reduce radon progeny concentrations and do not reduce actual radon concentrations. It is agreed that circulation of air enhances the mass transfer of radon daughters from the air to room surfaces and fan blades but there is disagreement among these sources if the majority is deposited on fan blades or walls. There is also disagreement in the fact that Holub (Ho79b) felt unattached particles led to increased plateout, whereas Hinds (Hi83) indicated that a greater majority of attached radon progeny plated out.

The mechanism of daughter product plateout is complicated and affected by such variables as aerosol concentrations, relative humidity, and fan speed. The following is one explanation of this complex phenomena. In household air, the majority of progeny almost immediately become attached to dust particles. The action of a fan serves to circulate the radon gas past household surfaces and the fan blades. The majority of progeny in the circulated air are already attached to aerosol particles. Plateout occurs to unattached progeny as they still hold a charge. Thus, the very instant an atom of ^{222}Rn decays to ^{218}Po , it can plateout on the surface of a fan blade or on other household surfaces. This decay must take place immediately adjacent to the fan blades or other household surfaces or it will become attached to an aerosol particle before having a chance to do so.

Humidity affects the plateout of progeny on fan blades as follows. Under highly humid conditions, a dew point can exist on the surface of the fan blades. Tiny water droplets are formed on the surface of the fan blades and progeny formed at the very instant they are passing the fan blade adhere to these tiny water droplets. These water droplets prevent the charged progeny from actually becoming attached to the fan blade. Evaporation takes place, releasing the progeny to the household air. Thus, humid conditions retard progeny plateout onto fan blade surfaces. Under low humidity conditions, dew point conditions are less likely to exist and plateout of unattached progeny can occur.

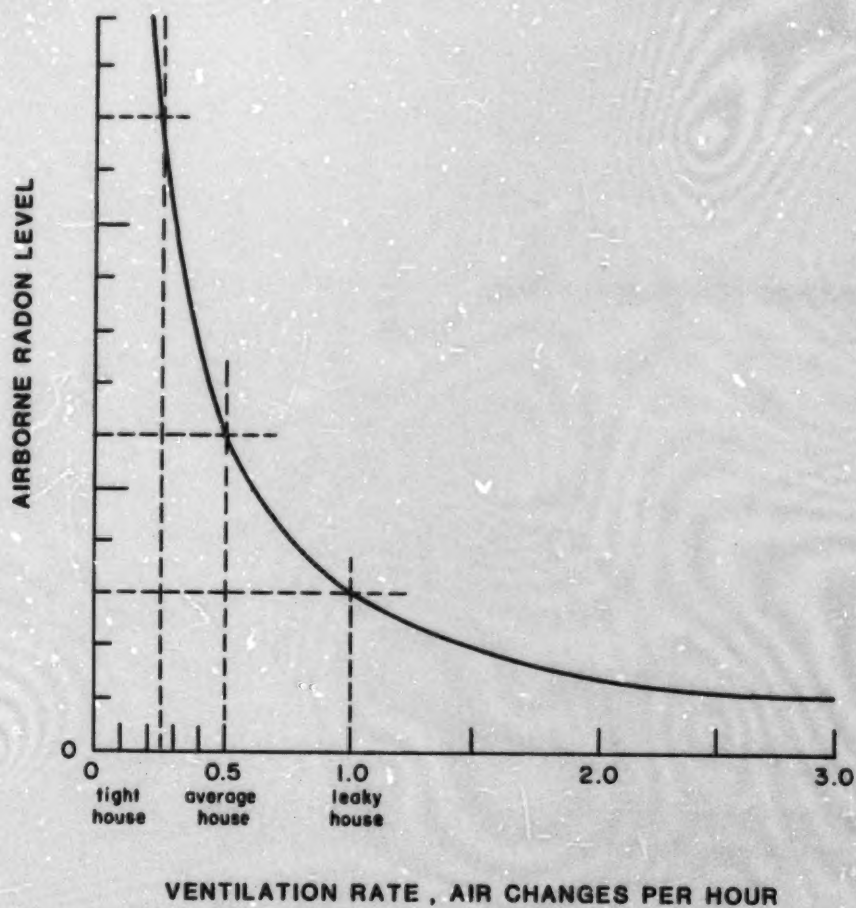
The costs associated with increased circulation include the capital cost of the box or ceiling fans, as well as the added energy usage to operate these devices. In the case of the ceiling fan, the ventilation rate of the home is also increased which results in the loss of heat with the increased air turnover. Thus, during heating and cooling months, energy consumption may increase substantially. An estimate of this increased energy cost is made later in this section. No detailed capital and operating cost estimates for circulation could be found in the literature, however, they are believed to be minimal.

6.2.2 Ventilation

There are a variety of devices that can be used to increase the home ventilation rate. Devices evaluated include natural ventilation, forced air heating and air conditioning systems, central fan, combined electrostatic precipitator and outside exchange system, and ventilation combined with an air-to-air heat exchanger.

A most effective measure for reducing the levels of radon and radon daughters is simple ventilation or air exchange with radon-free (or radon-poor) air. As the household air exchange rate is approximately inversely proportional to the radon concentration, doubling the air exchange rate results in about a 50 percent reduction in the indoor radon concentration. Figure 6-1 illustrates the general relationship between the ventilation rate and the relative airborne radon level.

The costs associated with increased ventilation include added energy usage due to more frequent blower operation plus added maintenance costs for the air-circulation system. In homes without forced air heating, the costs may include capital investments in ventilation equipment (Mo80). The major drawback with the use of increased ventilation for the control of airborne radon and radon progeny is the loss of heat with the rapid air turnover. Thus during heating and cooling months, energy consumption may increase substantially. An estimate of this increased energy cost is made later in this section.



Source (We82)

Figure 6-1

**AIRBORNE RADON LEVEL
versus VENTILATION RATE**

Natural Ventilation: Natural ventilation occurs when windows are opened and outside air is purposely allowed to circulate through the house. An experiment was performed to simulate natural ventilation and results are given in Table 6-3. Natural ventilation resulted in the removal of 94 percent of the radon and 91 percent of the radon progeny. This experimental data verifies the approximate inverse proportionality relationship between ventilation rate and radon concentration because as the ventilation rate is increased by a factor of 11, the indoor radon concentration decreases by a factor of 17.

Forced Air Heating and Air Conditioning Systems: Another source of household ventilation is from forced air heating and air conditioning systems. A study was conducted in a house to determine the reduction in radon and WL caused by operation of a central air conditioning system (EERF78). The house had been closed and the air conditioning system off for at least 12 hours prior to the beginning of the study. Measurements of radon and radon daughters were made prior to and at selected intervals for approximately 700 minutes after the air conditioning was turned on. Data presented in Table 6-3 are an average of two separate but duplicate experiments. After about 180 minutes of continuous running, 79 percent of the radon and 91 percent of the radon progeny are removed by air conditioning. This data verifies the inverse proportionality relationship since as the ventilation rate was increased by a factor of 5, the radon concentration was reduced by a factor of 4.9. However, the WL was reduced by a factor of 11. Increased reductions of radon progeny beyond that of simple dilution are assumed to be due to plate-out in ductwork due to forced air circulation.

Central Fan: The operation of a central fan can be used to increase the ventilation rate (EERF78). A study was conducted in a house to determine the reduction in radon and WL caused by operation of a central fan. The central fan system ran continuously during the experiment with no cycling. Air flow in the duct system was the same as in the air conditioning study just described.

TABLE 6-3
SUMMARY OF VENTILATION DATA

Type of Ventilation	Ventilation Rate (hr ⁻¹)		Rn Concentration (pci/l)		Rn Removal (%)	Working Level with Baseline Treatment		WL Removal (%)	Condensation Nuclei (#/cm ³)	
	Baseline	with Treatment	Baseline	with Treatment		Baseline	Treatment		Baseline	with Treatment
Air Conditioning	0.50	2.5	34	7	79	0.11	0.01	91	6x10 ³	3x10 ³
Central Fan	0.57	2.1	25	5	80	0.09	0.01	89	5x10 ³	3x10 ³
Natural Air Ventilation	0.50	5.4	25	1.5	94	0.11	0.01	91	1.7x10 ³	20-36x10 ³

NOTES: aWith treatment - Ventilation device was turned on which in turn increased the ventilation rate.

Source: (EER#78)

Data presented in Table 6-3 are an average of two separate but duplicate experiments. After approximately 180 minutes of operation, 80 percent of the radon and 89 percent of the radon progeny had been removed. The inverse proportionality relationship is again satisfied because as the ventilation rate was increased by a factor of 3.7, the radon concentration decreased by a factor of 5.

Combined Electrostatic Precipitator and Outside Exchange System: Guimond (Gu79) modeled a combined electrostatic precipitator and outside exchange system for WL reductions. The model assumes a flow rate through the system of 1.5 air changes per hour and about 25 percent makeup air. The model predicts a radon progeny reduction of 62 percent.

Ventilation Combined with an Air-to-Air Heat Exchanger: As stated earlier, one of the major drawbacks to ventilation systems for radon and radon progeny control is the loss of heated or cooled air. To reduce energy losses, air-to-air heat exchangers are used to recover much of the hot or cold air normally lost to the environment during ventilation. Nazaroff (Na80) conducted a series of experiments to assess reductions in indoor radon concentrations resulting from the use of increased ventilation rates through the air-to-air heat exchanger. These results are summarized in Table 6-4. Actual radon reductions agreed well with those predicted by the inverse proportionality ratio.

Capital and Operating Cost Comparison:

Capital Costs - The capital costs for the particular ventilation system selected depends upon existing equipment in the home. Obviously, natural ventilation only employs the opening of windows and would not entail additional capital cost. If a home is already equipped with forced air heating and air conditioning, no additional capital cost would be incurred. However, if another system already exists (steam heat, convective heating), expensive ductwork would have to be installed in addition to a central blower. If a central fan is not currently installed, the capital cost would be

TABLE 6-4

VENTILATION COMBINED WITH AN
AIR-TO-AIR HEAT EXCHANGER

<u>Air Exchange Rate (hr⁻¹)</u>	<u>Radon Concentration (pCi/l)</u>	<u>Predicted Rn Reduction from Ventilation Ratio (%)</u>	<u>Actual Rn Reduction (%)</u>
0.07	33	46	30
0.13	23	68	72
0.40	6.4	33	34
0.60	4.2		

the cost and installation of the central fan. The additional capital cost incurred from the installation of a combined electrostatic precipitator and outside exchange system would be the cost of the electrostatic precipitator plus the cost of the ventilation, ductwork and central blower if it does not currently exist. The additional capital cost incurred from the installation of ventilation with air-to-air heat exchanger would be the cost of the heat exchanger and blower and ventilation ductwork if it does not currently exist.

Capital cost information was available in the literature for an electrostatic precipitator and air exchange unit and an air-to-air heat exchanger system. This information is summarized in Table 6-5.

Operating Costs - The operation and maintenance (O&M) cost of a ventilation rate increase is the cost of heating or cooling the extra air which flows through the house, any additional energy costs associated with a forced air system, and any maintenance costs on any additionally installed equipment. As a practical example, the additional heating cost of a 50 percent reduction in the radon concentration in a house through doubling the air change rate is calculated as follows:

Basis: Initial air exchange rate = 0.5 hr⁻¹

V_{house} = 375,000 liters

Assume = 4,800 degree (°C) days/yr of heating

Fuel oil cost = \$1.20/gallon

Heat content = 150 x 10⁶ J/gallon

Specific heat dry air = 1,400 J/°C-m³

Furnace efficiency = 75%

An additional (375,000 liters)(1000 liters/m³) = 187.5 m³/hr of air must be heated to reduce the radon concentration by 50 percent (We82).

(0.5/hr)(375 m³)(24 hrs/day)(4800 °C/0.75)(1400 J/°C-m³)

(1 g/150 x 10⁶ J)(\$1.20/gallon) = \$320/yr

TABLE 6-5

ESTIMATED CAPITAL AND OPERATING COSTS OF
VENTILATION CONTROL MEASURES^a

Control Measure	Capital Cost	Annual Maintenance Cost	Annual Electrical Cost	Total Average Annual Operating Cost	Source
Electrostatic Precipitator and Air Exchanger ^b	1,400	40+	125	165+	Gu79
Air-to-Air Heat Exchangers ^c :					
60 m ³ /hr, 30 watts	100	10 ^d	15	25	We82
190 m ³ /hr, 90 watts	500	50	40	90	We82
420 m ³ /hr, 240 watts	1,400	140	110	250	We82

110

^aCosts updated to December 1983 dollars using the CE Plant and Equipment Cost Index.
^b375 m³ of house volume.

^cBasis: 4800 degree (°C) days/year, 375 m³ of house volume.

^dEstimated at 10% of capital cost.

These costs do not include the extra heating or cooling cost due to increased air exchange rates.

The cost of heating the same additional 187.5 m³ of air/hr if one installed a heat exchanger that is 70 percent efficient (We82) is calculated as follows:

Basis: 90 watt unit can supply needed 0.5 hr⁻¹ air exchange rate

Blower cost = \$40/yr

Maintenance cost = \$50/yr

$(\$320/\text{yr})(0.3) + \$40/\text{yr} = \$136/\text{yr}$

Thus, the heat exchanger would pay for itself in ventilation air heat savings under these hypothetical conditions in 3.5 years.

One can see that the O&M costs are dependent on the initial air exchange rates, the final exchange rate required to achieve the desired radon reduction, energy costs, equipment efficiency, and geographical heating or cooling requirements.

6.2.3 Air Cleaners

Air cleaners are designed to remove particulates from the circulating air of building interiors without the accompanying heat loss. The type of air cleaner used depends upon the particle size and shape, specific gravity, concentration of the particulates, and the desired removal efficiency (Gu79). Two major types of air cleaners are filtration units and electrostatic precipitators.

Air filtration is the separation of particulate matter from the air by the use of porous medium. Capital and O&M cost estimates for household filtration devices were not available in the literature reviewed.

Electronic air cleaners use electrostatic precipitation principles to collect particulate matter. Residential electrostatic precipitators operate on standard house current and with normal operation use electricity at the same rate as a 50-watt lightbulb (Gu79). The capital and O&M cost of an electronic air cleaner coupled with an air exchanger was given in Table 6-5. The costs in 1983 dollars were projected to be \$1,400 and \$165/yr, respectively.

A number of studies have been performed to evaluate the performance of air cleaners for radon progeny removal from building interior. Table 6-6 summarizes this data. Actual experimental data indicates that filtration devices can remove up to 90 percent of the radon progeny while electrostatic precipitators were proven 73 to 95 percent efficient. It must be stressed that air cleaners only remove particulates from air (.,only radon progeny), not radon. A study was performed by George (Ge80a) that characterizes the size of aerosol particles to which radon daughters are attached. From measurements of particle size in four residences, the average fraction diameters are bimodally distributed around 0.125 and 0.007 μm . Figure 6-2 illustrates three typical bimodal distributions. Since typical filters are very efficient in collecting particles 0.1 μm and larger, the majority of attached radon progeny would be removed. Removal of radon progeny affects the final equilibrium ratio of radon to the radon progeny. A description of the factors that affect the performance of these air cleaning devices follow.

Air cleaners reduce WLs by three mechanisms:

- 1) They collect attached and unattached decay products directly
- 2) They create air circulation that causes an increase in plate-out to the room surfaces
- 3) They remove aerosol particles thereby increasing the fraction of unattached radon decay products and facilitating plate-out to the chamber surfaces because of the much greater diffusion coefficient of unattached decay products compared to attached (Hi83).

Hinds (Hi83) evaluated the performance of an air filter and an electrostatic precipitator for radon progeny removal. Experimental results are presented in Table 6-7. These results indicate that at an air change rate of 0.52 hr^{-1} , the electrostatic precipitator produced 81 percent of its WL reduction by direct capture and the remainder, 19 percent by enhanced plateout. The filter produced 82

TABLE 6-6
SUMMARY OF FILTRATION DATA

<u>Treatment Technology</u>	<u>Radon Progeny Removal (%)</u>	<u>Source</u>
Electrostatic Precipitator	38 (modeled)	Gu79
HEPA Filter	38 (modeled)	Gu79
Combined EP and 25% Outside Makeup Air	62 (modeled)	Gu79
Electrostatic Precipitator	83-95	Mi80
Filtration	90	We82
Electrostatic Precipitator	73	Hi83
Filtration	89	Hi83

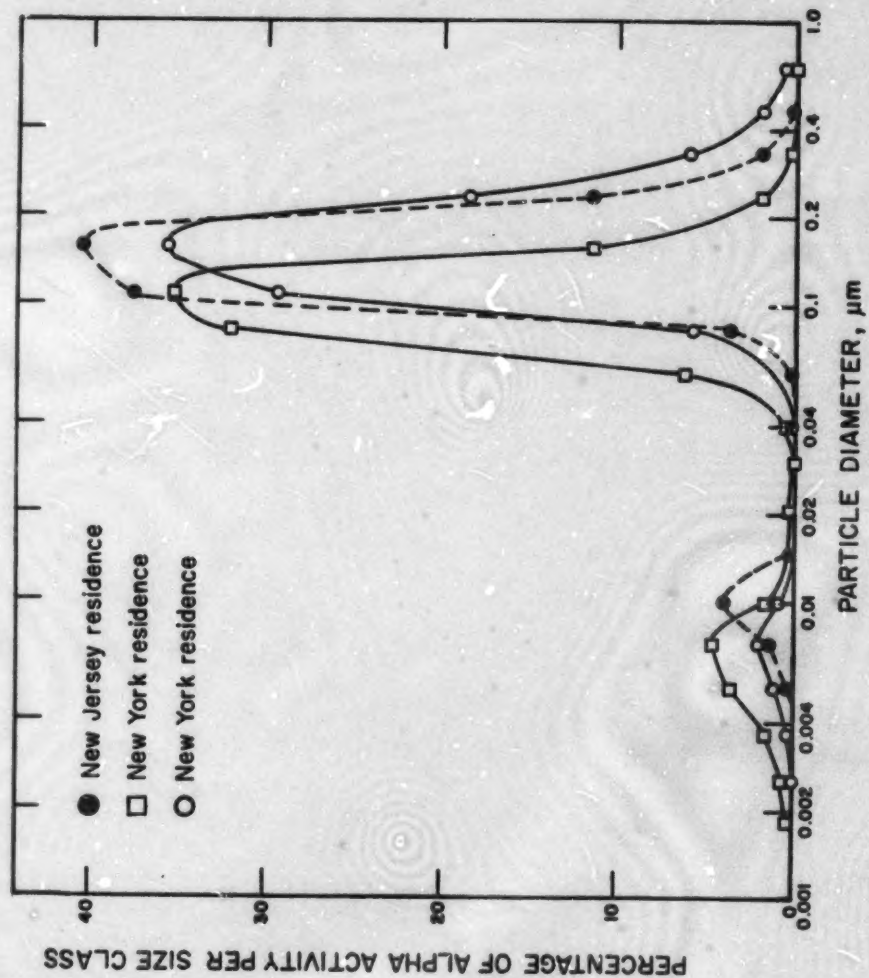


Figure 6-2

Histograms of aerosol size to which
 Radon progeny are attached

(Source Ge80a)

TABLE 6-7
AIR TREATMENT SYSTEM PERFORMANCE

	Filter				Electrostatic Precipitator			
	Ra A	Ra B	Ra C	WL	Ra A	Ra B	Ra C	WL
Attached Activity:								
Initial Conc. (pCi/l)	10.8	9.3	8.4		10.8	9.3	8.4	
% Removal	89	98	97		27	77	93	
Unattached Activity:								
Initial Conc. (pCi/l)	5.2	2.7	1.3		5.2	2.7	1.3	
% Removal	0	64	93		43	57	50	
Total Activity:								
% Removal	60	73	96	89	32	73	87	73

NOTES: Ra A = ^{218}Po ; Ra B = ^{214}Pb ; Ra C = ^{214}Bi

Source: (Hi83)

TABLE 6-8
CHARACTERISTICS OF AIR TREATMENT DEVICES

Air Treatment Device	Flow Rate (m^3/s)	Treatment Device Effective Air Exchange Rate (hr^{-1})	Power (W)	Collection Efficiency of 0.1 μm Particles (%)
HEPA Filter	0.11	5.1	110	70
Electrostatic Precipitator	0.11	5.1	-	>99.9

Source: (Hi83)

percent of its WL reduction by filtration and 18 percent by the indirect effort of enhanced plateout. The characteristics of the air treatment devices are given in Table 6-8. This data indicates that under the experimental conditions, both devices exchanged the air in the experimental chamber 5.1 times per hour or once every 12 minutes.

The effective air exchange rate for a treatment device is important when dealing with radon progeny removal because of the short time (3.05 min) required for ^{218}Po to come into equilibrium with radon. Thus, if it were desired to reduce the concentration of ^{218}Po by a factor of 10, a filtration system - either electronic or mechanical - would require an effective air exchange rate equal to twice the volume of the building interior each minute. Fortunately, the radionuclides of primary importance from a radiation-dose point of view (beta emitters) are ^{214}Pb and ^{214}Bi . Since these radionuclides have a half-life of 26.8 and 19.7 minutes respectively, a flow-through filtration system in which the recirculation time is less than 30 minutes can provide significant reductions in their airborne concentrations (Mo80). This explains why the removal efficiencies for ^{214}Pb and ^{214}Bi are so much greater than those of ^{218}Po as previously illustrated in Table 6-7.

Table 6-7 results also indicate that filters and electrostatic precipitators are much more efficient in their removal of radon progeny when it is in the attached rather than the unattached form.

The aerosol concentration in the home also affects the removal efficiency of the filter. Jonassen (Jo82) reported that at high aerosol conditions (10^{12} particles/ m^3) a filter is about 70 percent efficient, at medium aerosol conditions ($3-5 \times 10^{10}$ particles/ m^3) about 87 percent efficient, and at low aerosol conditions ($1-5 \times 10^8$ particles/ m^3), close to 100 percent efficient. These results indicate that at high aerosol concentrations, filtration is the only mechanism removing radon progeny but as aerosol concentrations are reduced, plateout in addition to filtration aid in radon progeny removal.

This brief review of the factors that influence radon progeny removal with the use of air cleaners illustrates the complexity of the problem. During filtration, none of the radon is removed, but microscopic particulates such as smoke and fumes are removed, resulting in fewer particles to which the continually-produced radon progeny can become attached. In an unattached form, the radon progeny are much more completely deposited in airways when inhaled, so the net reduction in progeny concentrations may be nullified when the amount adhering to the lung passageways is considered (We82). Thus, the eventual health implications of filtration are not clear at this time.

This review of air cleaning technology results in the following conclusions:

- 1) Air cleaners do not reduce radon concentrations; they only reduce radon progeny concentrations.
- 2) Although radon progeny removal using electrostatic precipitation is not as efficient as filtration, it resulted in much lower concentrations of unattached activity.
- 3) Filtration in conjunction with aerosol concentration control could prove a highly efficient radon progeny control technology.
- 4) In homes already equipped with forced air heating and cooling, the installation of a filtration device could prove most cost-efficient for the control of radon progeny.

6.2.4 Charcoal Adsorbers

Only limited information is available on the use of charcoal adsorbers for the removal of radon gas. Charcoal adsorption of ^{222}Rn was first developed for analytical testing and is optimal at -80°C . Care must be taken not to contact the column with water vapor or carbon dioxide as they will saturate the column and make

it ineffective for radon removal. Thus, a household radon removal system based on these operating conditions would be highly impractical. However, in 1974 Thomas patented a cyclic adsorption-desorption system to remove radon from ambient air.

In this cyclic system, radon is first removed from air by sorption on a charcoal bed at room temperature. When the charcoal becomes saturated, it is heated, the radon desorbed, and the bed cooled and reused. Continuous cleansing of the air is assured by the use of two adsorption beds in alternation. The advantage of charcoal adsorption over simple filtration is that it allows both radon and radon daughters to be removed rather than just radon progeny. Such a system requires a lower throughput than a radon daughter filtration system to accomplish the same dose reduction. Preliminary calculations indicate that as little as 45 kilograms of activated charcoal, operated on a cyclic basis, would be adequate for removing airborne radon emanating from the basement of a home. One drawback to the system is that other contaminants within household air (e.g. cooking vapors) would poison the charcoal bed and shorten its useful operating cycle. However, the activated charcoal can be regenerated thermally with only about a 10 percent loss due to attrition. Major cost items would include the initial capital cost plus installation and the operational expenses associated with recharging the bed on, roughly, an hourly basis. It is estimated that the installation and operating costs of such a system, once developed commercially, would be intermediate between a simple filtration system and a home air conditioning system (Mo80). No information was given on the radon removal efficiency of a charcoal adsorber.

6.2.5 Chemical Reaction

Although radon is generally considered to be inert, it reacts spontaneously at ambient temperature with a number of solid oxidizing reagents. Examples of useful oxidizing agents include dioxygenyl salts, fluoronitrogen salts, and halogen fluoride-metal

fluoride complexes. A method for the collection of radon from air, using either di-oxygenyl hexafluoroantimonate ($O_2+SbF_6^-$) or hexafluoroiodine hexafluoroantimonate ($IF_6+SbF_6^-$) reagent has been developed by Stein (St72, St82).

The radon removal system consisted of passing the radon laden air through a drying bed and then through a bed of the oxidizing reagent. This method captures radon as a non-volatile product ($RnF+SbF_6^-$). In tests with radon-air mixtures containing 45 to 210,000 pCi/l of ^{222}Rn , more than 99 percent of the radon was retained by beds of powders and pellets.

Both reagents, $O_2+SbF_6^-$ and $IF_6+SbF_6^-$, are stable and can be stored at room temperature in sealed Teflon containers. However, they are decomposed by moisture and must be used in conjunction with desiccants in humid atmospheres. Unlike other radon oxidizing agents which react violently with liquid water, $O_2+SbF_6^-$ and $IF_6+SbF_6^-$ have been shown to hydrolyze smoothly and exothermically. They are therefore considered to be the safest oxidants available for radon removal at present. One potential problem with the use of these two oxidants is that reactions of these compounds with carbon monoxide, methane, sulfur dioxide, nitric oxide, and other components of diesel exhausts have been reported (St82).

To date, this method of radon removal has only been evaluated for analytical purposes. No information was reported on radon removals per weight of oxidizing agent or the cost of these oxidizing agents, so a capital and operating cost estimate for a household model is not possible. Another drawback to the use of this type of oxidizing agent is that fluorine compounds could possibly be released. More technical information is needed to fill the data gaps on these oxidizing agents before a definite assessment as to their usefulness can be made.

6.2.6 Space Charging

Another technology that could possibly be used for the removal of radon progeny from household air is space charging. It is known

that, if an excess quantity of ions of one charge is added to a space containing an aerosol, mutual repulsion of the particles will lead to their removal (Mo80). No current information could be found on the use of this technology for radon progeny removal.

6.2.7 Summary

A comparison of the costs and efficiency of each technology evaluated for removal of radon and radon progeny is presented in Table 6-9. For some of the technologies, a sufficient data base to evaluate efficiency and cost is not available.

TABLE 6-9

SUMMARY OF TECHNIQUES TO ACHIEVE
REMOVAL OF ^{222}Rn AND PROGENY FROM AIR IN HOMES

Technology	Potential Removal Efficiency ^{222}Rn	Rn Progeny	Costs in 1983 Dollars		Comments
			Capital	Annual O&M	
Circulation (fans)	0	50-63%	20-150	-	Assuming no ventilation rate change
Ventilation: Natural (open window)	94%	91%	0	0	Increase ventilation rate by factor of 11; neglects heat/cooling loss
Forced Air Heating & Cooling	79%	91%	0	0	Costs are routinely incurred.
Central Fan (increase vent rate 3.7 times)	80%	89%	20-150	320	Annual costs for additional heating (only) based on doubling ventila- tion rates
Combined ESP/outside 0 exchange system	0	62%	1400	165+	
Ventilation combined with air-to-air heat exchange	34-87%	-	100-1400	25-250	Costs dependent on ventilation rate achieved
Air Cleaner: Filtration	0	<90%	-	-	
Electrostatic Precipitator	0	73-95%	-	-	
Charcoal Adsorber	-	-	-	-	
Chemical Reaction	99	-	-	-	Experimental
Space Charging	-	-	-	-	No information

- = Insufficient Data

^aBased on mathematical modeling

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